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Cast iron component failure: A metallurgical investigation

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Abstract

A fractured nutcracker was examined for determining the root cause/s for premature fracture/failure. This is one of the common tools used typically for cracking hard nuts. In this study, metallurgical failure analysis techniques namely, visual inspection, optical microscopy, SEM, and hardness tests were used in investigating the broken product. From the metallurgical analysis, it was determined that the combined effect of low carbon equivalent and presence of inclusions contributed to the sudden fracture of the nut cracking tool.

Keywords: Cast iron component, Hardness tests, Optical microscopy, Scanning electron microscopy; Fractography.

1. Introduction

Metallic nutcrackers are used to crack hard shells of the nuts without damaging the inner nut. Usually it is made of a quality cast metal with chrome plating. Long handles provide leverage for easier cracking. It can be used for all sizes of nuts from small hazelnuts to large walnuts. Nutcracker that measures about 4 inch in length was made of gray cast iron which is an important engineering material. This is due to its relatively low cost and useful engineering properties such as excellent machinability at hardness levels that have good wear resistance, resistance to galling under restricted lubrication, and excellent vibrational damping capacity [1].

In the present case, a broken nut-cracking tool was subjected to metallurgical investigation to determine the root cause/s for its fracture.

2. Material and methods

2.1 Material

The material used in the currently investigated tool was a gray cast iron with 3.0% carbon and 1.8% silicon. The detailed composition is given in Table 1.

Table 1.
Chemical composition of the investigated component

Elements	C	Si	Mn	P	S
%Wt.	3.0	1.8	0.6	0.09	0.08

Gray cast irons usually contain 2.5 to 4% **C**, 1 to 3% **Si**, and additions of manganese, depending on the desired microstructure.

2.2 Casting and inoculation

Gray irons are a group of cast irons that form graphite flakes during solidification, in contrast to the spheroidal graphite morphology of ductile irons. The investigated gray cast iron tool was produced by sand casting technique. Green sand molding is the most widely used technique for producing gray iron castings. Gray iron expands slightly because of the formation of graphite during eutectic solidification. It is important when producing gray iron castings that the mold hardness is sufficient to withstand the eutectic expansion of the gray iron. Silicon is used as an inoculant/graphitizer that breaks up the cementite structure to get free carbon in the form of graphite flakes. Since silicon is a graphite stabilizing element in cast irons, relatively high silicon content is required to promote graphite formation. The solidification rate is also an important factor that determines the extent to which graphite forms.

2.3 Heat treatment

The flake graphite in gray irons is dispersed in a matrix with a microstructure that is determined by composition and heat treatment. The usual microstructure of gray iron is a matrix of pearlite with the graphite flakes dispersed throughout. The heat treatment of gray irons can considerably alter the matrix microstructure with little or no effect on the size and shape of the graphite achieved during casting. The matrix microstructures resulting from heat treatment can vary from ferrite-pearlite to tempered martensitic structure. However, even though gray iron can be hardened by quenching from elevated temperatures, heat treatment is not ordinarily used commercially to increase the overall strength of gray iron castings because the strength of the as-cast metal can be increased at less cost by reducing the silicon and total carbon contents or by adding alloying elements. The most common heat treatments of gray iron are annealing and stress relieving.

Chemical composition is another important parameter that influences the heat treatment of gray cast irons. Silicon, for example, decreases carbon solubility, increases the diffusion rate of carbon in austenite, and usually accelerates the various reactions during heat treating. Silicon also raises the austenitizing temperature significantly and reduces the combined carbon content (cementite volume). Manganese, in contrast, lowers the austenitizing temperature and increases hardenability. It also increases carbon solubility, slows carbon diffusion in austenite, and increases the combined carbon content. In addition, manganese alloys and stabilizes pearlitic carbide and thus increases the pearlite content.

Annealing

Annealing is the most frequently used heat treatment for gray cast irons, with the possible exception of stress relieving. The annealing of gray cast iron involves heating gray iron to a temperature high enough to soften it and/or to eliminate massive eutectic carbides, thereby improving its machinability. This heat treatment reduces mechanical properties significantly. It reduces the grade level approximately to the next lower grade: for example, the properties of a class 45 gray iron will be diminished to those of a class 35 gray iron. The degree of reduction of properties depends on the annealing temperature, the soaking time at annealing, and the composition of gray cast iron. Gray cast iron is commonly subjected to one of three annealing treatments, each of which involves heating to a different temperature range. These treatments are ferritizing annealing, full annealing, and graphitizing annealing. Ferritizing annealing is carried out to convert pearlitic carbide to ferrite and graphite for improved machinability. For most gray cast irons, a ferritizing annealing temperature between 700°C and 760°C is recommended. Full annealing is usually performed at temperatures between 790°C and 900°C. This treatment is used when a ferritizing anneal would be ineffective because of the high alloy content of a particular cast iron. Graphitizing annealing is chosen to convert massive carbide to pearlite and graphite, although in some applications it may be desired to carry out a ferritizing annealing treatment to provide maximum machinability.

Normalizing

Gray cast iron is normalized by heating to a temperature above the transformation range, soaked at this temperature for about 1 hour per inch of maximum section thickness or diameter, and cooled in ambient air to room temperature. Normalizing may be used to enhance mechanical properties, such as hardness and tensile strength. The temperature range for normalizing gray cast iron is between 885°C to 925°C. Higher normalizing temperatures increase the carbon solubility in austenite. The alloy composition of a gray cast iron also influences carbon solubility in austenite. Faster cooling results in small pearlite spacing, higher hardness, and higher tensile strength. At a higher cooling rate, the transformation of the structure is likely to be partial or fully martensite.

2.4 Rockwell hardness test

Rockwell hardness test is the most common method used to measure hardness because of its simplicity and requiring no special skills. The hardness number is determined by the difference in depth of penetration resulting from the application of an initial minor load followed by a larger major load. Rockwell hardness scale C was used in the present investigation with 10 kg and 150 kg as minor and major loads, respectively.

Hardness tests were performed on the presently investigated component using a standard digital Rockwell hardness tester (LECO) according to ASTM E18-07 standard. Rockwell hardness test (HRC) was carried out at locations close to the fracture region to assess the hardness of the failed casting.

2.5 Optical microscopy

The specimen surface must first be ground and polished to a smooth and mirror-like finish. This is accomplished by successively finer abrasive papers and powders. The microstructure is revealed by a surface treatment using an appropriate chemical reagent in a procedure called etching.

Optical microscopy was performed to investigate the basic microstructure of the nutcracker tool. This was done on well-polished and etched samples using Olympus optical microscope and HiRox digital microscope - KH 7700 model. Nital (2 ml of HNO_3 in 100 ml water) was the etchant used for revealing the microstructure.

2.6 Scanning electron microscopy

The fractured surface features were studied using SEM-LEO 1430 VP and Phenom models. The fractured surfaces were cleaned thoroughly using acetone in an ultrasonic stirrer before examination. EDX attachment to SEM was also used to perform the elemental composition of the inclusions present in the investigated product.

3. Results and discussion

3.1 Visual examination

The broken nut cracker component is shown in Fig. 1. Visual examination of the fractured tool indicated gray fracture surface indicative of exposed graphite in gray cast iron. Gray cast iron is formed when the carbon in a given alloy exceeds the amount that can dissolve in the austenite and precipitates as graphite flakes.

Fig. 1. Fractured gray cast iron nut cracker demonstrating a gray fracture surface

3.2 Carbon equivalent

For cast irons, the main elements of the chemical composition are carbon and silicon. High carbon content increases the amount of graphite or Fe_3C. High carbon and silicon contents increase the graphitization potential of the iron as well as its castability. The combined influence of carbon and silicon on the structure is usually taken into account by the carbon equivalent (**CE**): CE = %C + 0.3×(%Si+%P). A high cooling rate and a low carbon equivalent favours the formation of white cast iron whereas a low cooling rate or a high carbon equivalent promotes gray cast iron [2, 3]. Gray irons usually contain 2.5 to 4% **C**, 1 to 3% **Si**, and additions of manganese, depending on the desired microstructure. Sulphur and phosphorus are also present in small amounts as residual impurities. The composition of gray iron must be selected in such a way to satisfy three basic structural requirements: graphite shape and distribution, carbide-free (chill-free) structure, and the matrix. Irons with a carbon equivalent of 4.3 are considered to be of eutectic composition, though most gray irons are hypoeutectic (CE less than 4.3). Nearly all of the mechanical and physical properties are closely related the CE value.

Chill testing provides the opportunity to evaluate and change the properties of the gray iron melt to make it consistent with expectations. Control of the chilling tendency is an important aspect of gray iron metallurgy. Important considerations in the production of gray iron are the carbon/silicon ratio, pouring and cooling temperatures, and the alloying and residual elements in the iron melt [4-8]. The presently investigated gray iron had a CE of 3.6, that is hypoeutectic which is considered as a lower value. Normally, lower the CE, higher the tendency for chill. This clearly has an influence on the conditions of solidifications and in turn the microstructure. Rockwell Hardness was found as 55 HRC. The relatively higher value of hardness suggests that this casting has a predominantly martensitic matrix structure. This was confirmed by performing micro-indentation hardness test specifically on the matrix. The microindentation hardness (Knoop microindentation) value obtained was HK 624 that is approximately found to be equivalent to HRC 55 based on standard comparative charts.

3.3 Rockwell hardness

Rockwell Hardness was evaluated as 55 HRC, average of 5 readings taken on the cross section of the broken component.

3.4 Optical microscopy

There are usually five graphite flake distributions in gray cast iron defined as A,B,C,D, and E types. Type A flake graphite (random orientation) is preferred for most applications. In the intermediate flake sizes, type A flake graphite is superior to other types in certain wear applications such as the cylinders of internal combustion engines. Type B flake graphite (rosette pattern/groupings) is typical of fairly rapid cooling, such as is common with moderately thin sections (about 10 mm) and along the surfaces of thicker sections, and sometimes results from poor inoculation. In the presently investigated tool, the structure is of a B-type which confirms a relatively rapid cooling mostly due to relatively lower value of CE that promotes chilling tendency by the formation of martensite as demonstrated in Fig 2.

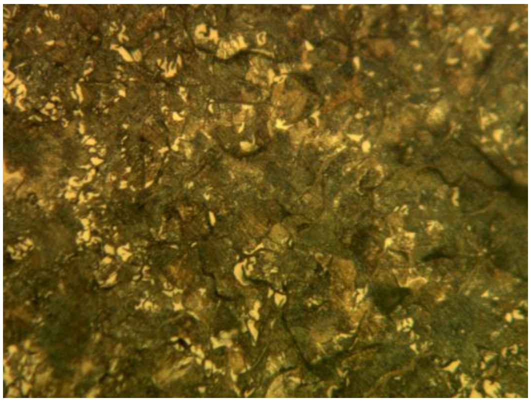

Fig. 2. Micrograph showing graphite flakes in a predominantly harder (martensite) matrix

3.5 Fracture morphology

SEM fractographs 3 clearly indicates the brittle/cleavage type of fracture indicative of the rapid solidification process the product has experienced. Figure 4 demonstrates the presence of inclusions (inclusions are undesired brittle compounds usually made up of metallic oxides and/or sulphides) that presumably provided the sites/regions for crack initiation and crack propagation leading to final fracture [9]. The presence of these inclusions was confirmed using EDX analysis (with SEM) and was reported as a combination of sulfide and oxide inclusions. These inclusions were noticed only on the broken/fractured surface.

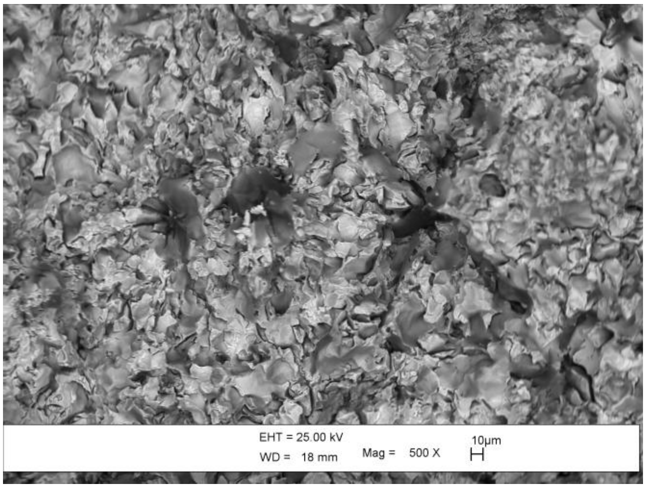

Fig. 3. Fracture surface demonstrating brittle fracture showing rosette pattern

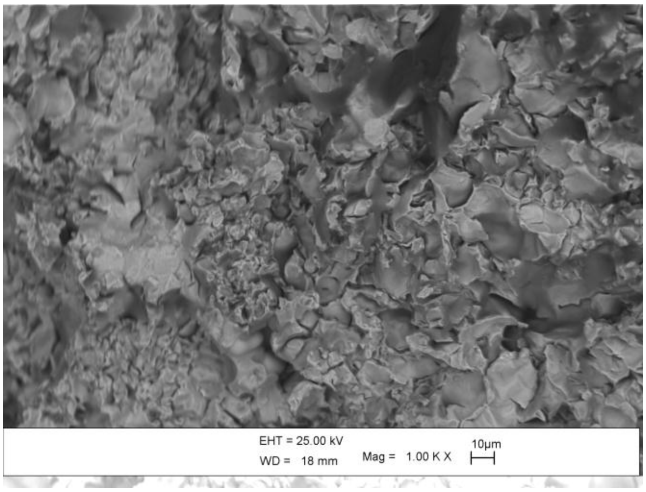

Fig. 4. Fracture surface demonstrating the presence of inclusions and cracking

4. Conclusions and recommendations

The root cause for the premature fracture of nut cracker was the lower carbon equivalent in the cast iron component. The presence of certain impurities also seemed to have contributed to the brittleness of the gray cast iron product. It was recommended to maintain the carbon equivalent to a value at about the eutectic composition to have a desired type of graphite flake distribution. This needs to be followed in all the melts to control the strength/hardness thereby ensuring the minimum level of toughness in the product. Inoculation is advised as well to produce changes in graphite distribution, improvements in mechanical properties, and a reduction in chilling tendency. Chill test is mandatory to assess the mechanical properties of the gray iron casting.

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