The Effect of Increasing Silicon on Mechanical Properties of Ductile Iron

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Abstract. Ferritic-pearlitic ductile iron has variation in hardness while the ferritic ductile iron has homogenous hardness. Ferritic-Pearlitic ductile iron has a wide range of hardness that varies between 170-230 HB. Due to variation in hardness, it is difficult to machine ferritic-pearlitic ductile iron as compared to ferritic ductile iron. To overcome this issue, it is desirable to get ferritic microstructure without compromising the mechanical properties of ductile iron. Silicon is a ferritic stabilizer and it strengthens the ferrite phase through solution hardening. Current work is done to see the effect of silicon content on the mechanical properties of ductile iron. The silicon content is increased from 2.1% to 3.6% in different experiments to examine, and then evaluated its effect on ductile iron. It is observed that the increase in silicon content increases the ferrite phase and decreases pearlite phase, resulting in reduced tensile strength and an increase in elongation. However, further increase in the silicon content resulted in increased tensile strength as well as in percentage elongation. Effect of silicon on percentage elongation, hardness, and impact strength are observed in these experiments. Moreover, the effect of silicon on microstructure in all experiments is also studied which has a direct impact on mechanical properties of ductile iron.

1. Introduction

Ductile iron is an alloy that contains spheroidal graphite nodules which gives ductility to it. Ductile iron is also known as SG iron or Spheroidal Graphite Iron. Many of the automotive parts are now manufactured using ductile iron. K. D. Mills added magnesium in grey cast iron in the form of Cu-Mg alloy at International Nickel Company in 1943. Keith Mills observed that there were no flakes rather graphite nodules taken their place in the microstructure [1]. To achieve good quality of ductile iron, sulphur and phosphorus content must be minimized, and their level is to be kept less than 0.03 wt.% sulphur and 0.1% phosphorus. Other trace elements should be kept low to make perfectly round or spherical nodules [2]. Carbon, Carbon equivalent, Silicon, Manganese, Aluminum and phosphorous are the significant components in the production of ductile iron and all these elements should be controlled carefully [3].

According to ISO 1083 the ductile iron grade EN-GJS-400-15 has ferritic microstructure (A single phase matrix) [4]. This category of ductile iron has uniform hardness than ferritic-pearlitic ductile iron (Two phase ductile iron). Casting made from ductile iron grade EN-GJS-500-7 has a range of hardness which varies between 170-230 HB [5]. This variation is because pearlite content is affected by cooling
rate [6]. Cooling rate would be different in different section of the casting by varying section thickness [7]. Castings with varying hardness leads to difficulties in machining. One way of reducing these variations is to choose a material that gives uniform hardness [8]. Ferritic ductile iron gives significantly more uniform hardness as compared to ferritic-pearlitic grades. Different components manufactured from ferritic-pearlitic grade often covers the entire of the standard hardness range. For example, ductile iron grade EN-GJS-600-3 has a hardness range between 190 – 270 HB [9] and are thus difficult to machine. So, a material with uniform hardness will have nearly the same hardness at different sections having different thickness [10].

Spheroidal cast iron (SG Iron) or ductile iron contains graphite nodules which are linked with thermally induced stress/strain [11]. Thermal cycling yields stress/strain cycles in the material through differential expansion and contraction causing due to temperature gradients. The amount of such thermal stress increases with increased temperature, larger range on which the temperature is changed/cycled and high rates of cooling and heating [12]. The effect of these thermal stresses on mechanical properties of ductile iron greatly depends upon size, shape and morphology of the graphite nodules [13].

Cracks due to thermal cyclic heating start from the surface [14]. Under cyclic heating or cooling, structural stability and oxidation resistance are very important parameters [15]. Therefore, SG iron with high silicon content is more suitable for high temperature applications. This is because silicon raises the eutectoid temperature, which leads to high temperature stability [16]. Austenite and ferrite stabilizers widen the respective phase fields. The effect of alloying elements on the Fe-Fe3C phase diagram is strongly reflected in the eutectoid temperature, which is raised or lowered by the alloying addition. The austenite stabilizers lower the eutectoid temperature, thereby widening the temperature range over which austenite is stable. Similarly, the ferrite formers raise the eutectoid temperature, thereby restricting the γ-phase field [17]. As silicon is a ferrite stabilizer, it raises the eutectoid temperature and improves the performance at elevated temperature [18]. In contrast, increasing the silicon content creates more thermal stresses on casting surface and eutectic cell boundaries under cyclic heating/cooling process [19]. Increasing the silicon content is suitable for high temperature applications, but too much silicon (above 6%) causes brittleness in the material which can result surface cracks on the surface of the casting [10]. This is due to the fact that too much silicon causes thermal stresses on casting surface during thermal cycling. It is confirmed from many reports that increasing the silicon content causes thermal cracking in the early stages of thermal cycling due to thermal stresses [20].

In ductile iron each graphite nucleus gives rise to a single graphite nodule, thus nucleation establishes the final nodule count. Accordingly, by increasing the nodule count in cast iron leads to increasing strength and ductility, improved microstructural homogeneity, and reduction in the chilling tendency [10]. Accordingly, it can be affirmed that graphite eutectic cells or nodules play a significant role in the exhibited properties becoming important factors in the foundry practice [21]. The cycling heating creates more thermal stresses on eutectic cell boundaries.

Ductile iron grade EN-GJS-500-7 is difficult to machine as compared to EN-GJS-400-15 due to pearlite content. Therefore, it is desirable to achieve the properties of EN-GJS-500-7 without compromising the difficulty of machining. In this research work, silicon content is increased in different experiments to analyze its impact on ductile iron, so that a single phase material can be obtained which has the properties of EN-GJS-500-7 and is relatively easy to machine.

2. Experimentation
To analyze the effects of silicon, its content was increased gradually in different experiments. Moulds were prepared using green sand moulding. As sand plays an important role in the sand casting process, different parameters were kept in control for a sound casting. Different sand test results are shown in Table 1. The sand was tested using methods of physical test for foundry sand IS 1918.

During experimentation, samples were prepared through the casting process using standard DIN EN 1563. Total eleven experiments were prepared in which silicon content was increased gradually and each experiment was repeated three times. The drawing of the casting prepared for the samples is shown in Figure 1, and the dimensions of the casting are given in Table 2.
Ductile iron was formed by treating molten metal having low sulfur content with FeSiMg additive. The resulting product was inoculated with ferro-silicon just before pouring it into moulds. Then experiments were carried out to investigate the effect of silicon addition in ductile iron. Composition of ductile iron is given in Table 3.

Table 1. Molding sand parameters

| No | Sand Test   | Range        |
|----|-------------|--------------|
| 1  | Compactability | 30-40%       |
| 2  | Specimen weight | 137-144 (g) |
| 3  | Compression strength | 12-26 N/cm² |
| 4  | Splitting strength | 6-8 N/cm²  |
| 5  | Permeability | 90-95        |
| 6  | Moisture | 3.0%-4.5%    |

Table 2. Separately cast sample drawing dimensions

| Dimensions | Millimeter (mm) |
|------------|-----------------|
| U          | 10              |
| V          | 100             |
| X          | 50              |
| Y          | 150             |
| z          | 200             |

Table 3. Ductile Iron composition

| Element | Percentage Composition |
|---------|------------------------|
| C       | 3.7-4%                 |
| Mn      | 0.2-0.3%               |
| Mg      | 0.03-0.05%             |
| S       | <0.02%                 |

C.E meter was used to measure C and Si percentage before pouring of ductile iron melt into moulds. C.E meter was accurate, up to ±0.2%. After Mg treatment ductile iron melt was inoculated. Composition of ductile iron, which includes carbon, silicon, magnesium, manganese and sulfur content was checked using q6 Columbus spark emission spectrometer after inoculation. This instrument gives improved stability and reproducibility. The accuracy of this instrument is ±0.1%. So silicon amount was measured at two stages. Before inoculation using C.E meter, and after inoculation using spark emission spectrometer. Only spectrometer results are given in Table 3. This is because silicon at the final stage is relevant. The composition of silicon before inoculation is not relevant at this stage.
The silicon content was increased in different experiments while keeping all other elements constant (Table 3) to study the effect of silicon on mechanical properties of ductile iron. Samples for tensile strength and microstructure were taken from the casting to check the mechanical properties and microstructure of each experiment. Tensile specimens were prepared using ISO 6892-1 standard. The drawing of the specimen is given in Figure 2. The strain rate was set to be 0.002s⁻¹. The impact testing samples were prepared according to standard test “Method for impact testing of Metallic Materials E23”. The drawing of the sample for the impact test is shown in Figure 3.

3. Results and discussion

Silicon is added to the ductile iron in different percentages to observe its impact on the tensile strength, % elongation and hardness. The silicon was added in these percentages: 2.17%, 2.18%, 2.2%, 2.21%, 2.27%, 2.3%, 2.45%, 2.8%, 3.17%, 3.45% and 3.63% for examination and evaluation. Carbon content in ductile iron was kept between 3.7 and 3.9 while the silicon content was increased from 2.1% to 3.6% in different experiments. As silicon content was increased, the ultimate tensile strength decreased (Figure 4) while elongation increased up to a certain point (Figure 5). As silicon content was increased from 2.1% to 2.3%, the tensile strength shows some variations, but after 2.3%, the tensile strength decreases up to 2.8% silicon content and then it started to increase again. Similarly, as the silicon content was increased from 2.1% to 2.3%, the elongation decreased up to 2.3% silicon content, but after that it started to increase as shown in Figure 5. This trend of tensile strength and elongation can be easily understood from the microstructures. It is clear from the Figure 8 that as silicon content was increased, the pearlite content in the microstructure shows a decreasing trend and an increase in the ferrite phase can be observed. This is the fact because of which a decrease in tensile strength is observed until 2.8% of the silicone content. After this silicon helps to strengthen the ferrite phase due to which tensile strength increased.

There are various parameters like melt temperature, composition, cooling rate, surrounding temperature, etc. which determines the mechanical properties of the material. All experiments are designed to maintain these parameters at a constant level in every experiment except silicon, but there is a possibility of small variations in these parameters that can affect the mechanical properties. To overcome this issue each experiment is repeated. To make the data easily understandable, an average value as well as standard deviation error bars is given in Figure 4 and Figure 5. Average of yield strength, tensile strength and elongation in Figure 4 and Figure 5 clearly show a significant effect of silicon on these properties which can be correlated with the microstructure in Figure 8.
As the silicon content was increased, hardness decreased as shown in Figure 6. This is because the ferrite was increasing, and pearlite content was decreasing. It was also observed that as the ferrite content was increased, and fully ferritic ductile iron was obtained, there was less variation in hardness as compared to when there was pearlite at lower silicon content. Five different points from the casting were selected on which hardness was measured to observe variation in hardness.

As the silicon content was increased, impact strength was increasing. This is because as silicon increases the pearlite content decreased and ferrite content increased which gives rise to impact strength. The pearlite consist of lamellar structure of ferrite and cementite and it is obvious that cementite (Fe3C) is more brittle as compared to ferrite. So, a material whose microstructure has higher pearlite content leads to lower the impact strength.

Figure 6. Hardness results

Figure 7. Impact test results at room temperature

Figure 8. Etched with 2% Nital. 1) Pearlite 45% ferrite 55% nodularity 80% 2) Pearlite 43% ferrite 57% nodularity 85% 3) Pearlite 40% ferrite 60% nodularity 90% 4) Pearlite 38% ferrite 62% nodularity 90% 5) Pearlite 35% ferrite 65%odule 80% 6) Pearlite 30% ferrite 70% nodularity 90% 7) Pearlite 25% ferrite 75% nodularity 85% 8) Pearlite 20% ferrite 90% nodularity 80% 9) Pearlite 5% ferrite 90% nodularity 90% 10) Pearlite 1% ferrite 90% nodularity 90% 11) ferrite 100% nodularity 90%
4. Conclusion
The silicon content was increased from 2.1% to 3.6% in different experiments. The tensile strength decreased when silicon content was increased up to 2.8%. Further increase in silicon content led to increase in tensile strength and yield strength. Hardness decreased gradually as silicon content was increased, and variation in hardness at different points was decreased as ferritic ductile iron was achieved. As the silicon percentage of ductile iron was increased, the pearlite content in the matrix become decreased and the ferrite portion increased led to improved impact value. By further increasing the silicon content, the matrix of ferritic pearlitic ductile iron becomes fully ferritic in which variation in hardness was less as compared to ferritic pearlitic ductile iron. It was observed that tensile strength and yield strength decreased up to a certain point and then start increasing. So by increasing the silicon content a fully ferritic ductile iron was achieved, which has a tensile strength of ferritic pearlitic ductile iron. Hardness showed a decreasing trend as pearlite was decreasing in the microstructure. So it will be easy to machine, as this material hardness and variation in hardness at different sections was low as compared to ferritic-pearlitic ductile iron. This high silicon ductile iron has better impact strength at room temperature as compared to ferritic pearlitic ductile iron, which was due to the low pearlite content in the microstructure.

5. References
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