Plasticity and Formability Controlling of Cast Iron Using Thermo-Mechanical Treatment

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Abstract There are different methods to improve the mechanical properties of materials such as, heat treatment, casting of alloying element etc. Thermo-Mechanical Treatment at different level of deformation is carried out to enhance the mechanical behavior of ductile cast iron. The tensile properties of the tested iron are determined at room temperature, 450°C, 750°C, and 850°C. However, the effect of testing temperature on ultimate tensile strength, strain hardening coefficient and ductility are investigated at different deformation speed; 1 mm/s, 5 mm/s and 25 mm/s. The results show that temperature affects significantly the deformation properties of the cast iron, the absorbed energy of the materials increases with the increase of deformation temperature and loading speed. The maximum softening is obtained for deformation temperature 850°C and smaller strain hardening coefficient 0.27. The deformation parameters temperature and speed make the deformation and flow behavior of this case of cast iron becomes like flow behavior of ductile steel.

Keywords: Thermo-Mechanical Treatment, ductile cast iron, flow behaviors, percentage elongation


1. Introduction

In order to change alloy shape and refine the microstructure, Thermo-mechanical treatment is carried out, it contains both application of heat and deformation process to an alloy. Malleable cast irons with flaked graphite and other cast iron with graphite inclusions of special shape are extensively used in manufacturing load-bearing machine design structure. The application of physic-mechanical and technological properties for these materials is often better than the corresponding characteristics of other metallic materials, including structural steels [1,2].

The mechanical properties of cast irons mainly depend on a lot of factors; the shape and sizes of graphite inclusions, the structure of the metallic base, and chemical composition.

With graphite inclusion in cast iron, its deformation under the mechanical loading on both micro and macro level is achieved by cracking, mainly the cracking sizes and intensity depend on shapes and sizes of graphite inclusion [3,4,5]. The serviceability of materials in many machine elements is affected by the process of cracking.

Chaus et al. [6] investigated, the effect of hot plastic deformation on the transformation of the primary (cast) microstructure of ductile cast iron with globular graphite (ductile cast iron). It has been shown that an increase in the degree of plastic deformation from 20 to 80% brings significant micro-structural changes in both the pearlitic-ferritic matrix and graphite inclusions of cast iron.

It was reported that, the plastic deformation is the main reason for formation of a specific microstructure [7-13] in ductile cast iron, with properties entirely different from those in the as cast state, which makes it likes special structural materials.

Lamashevskii and Makovetskii [14] analyzed the experimental data on the specific features of damageability, deformation, and strength of malleable cast iron obtained in testing tubular specimens under conditions of simple loading by axial forces and internal pressure, they obtained that the degradation of the structure of the material depends on the parameters of the stressed state.

The main objects of the present work are to enhance ductility and flow behavior of cast iron without change in the alloying chemical composition, using thermo-mechanical treatment technology. The ductility enhancement enlarges range of applications of cast iron in bulk metal forming technology such as; Forging, Rolling, and Extrusion.

2. Material Characterization

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Table 1. Chemical composition of the tested cast iron (Wt%)

<table>
<thead>
<tr>
<th>Elements Contents</th>
<th>C%</th>
<th>Si%</th>
<th>Mn%</th>
<th>P%</th>
<th>S%</th>
<th>Balanced Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.0-3.6</td>
<td>2.0-2.5</td>
<td>0.6</td>
<td>0.04 max</td>
<td>0.04</td>
<td></td>
</tr>
</tbody>
</table>

Ductile cast iron, which chemical compositions are listed in Table 1 is obtained from Egyptian iron and steel company at Helwan. The mechanical properties of the tested material are obtained through tension test at room temperature and cross head speed of 5 mm/min.

The tensile strength is measured as 827 MPa, yield stress 820 MPa and percentage elongation 2.3%.

3. Experimental Work

The tensile test specimens of cast iron are end threaded to avoid the slip during the test. The dimension and geometry of the specimens are shown in Figure 1. The specimens are subjected to axially loading using 10 ton universal testing machine. The thermo-mechanical treatment(T. M. T)parameters are exposure temperature and level of deformation, therefore the tensile specimen through the test are heated up to the required temperature (450°C, 750°C, and 850°C.) using the universals testing machine tube furnace and held at this temperature for 20 min; to ensure the homogeneity of temperature distribution along the specimen gauge length. The specimens are deformed up to different levels of uniform strain, (0%, 25%, 50%, 75% and 100%). These levels of deformation are measured using dial gauge supported against the movable cross platen. Tests are performed according to ASTM E8 [15].

![Figure 1. Thermo-mechanical treatment test specimen](image)

4. Results and Discussion

The thermo-mechanical treatment experimental matrix results are investigated for effect of temperature and deformation speeds on the ductility and strength of cast iron.

Figure 2 shows effect of temperature in thermo-mechanical treatment on flow behaviors of cast iron, as temperature increases strength of material decreases and ductility increase (see Figure 3a, Figure 3b) it is observed from the iron–carbon (Fe–C) phase diagram that as the cast iron heated below eutectoid temperature (727°C) the ferrite phase (α-iron) exists combined with cementite phase (Fe3C) [6]. The ferrite phase gives softening to the material, leads to appear small size pores and dimples in the microscopic structures of cast iron at heating below eutectoid temperature (450°C) (see Figure 5b), it can be assumed that the white phase is ferrite. Focus observation of (SEM) for deformation at ambient temperature, get that the cementite phase perfectly soluble in the iron matrix with ferrite one (see Figure 4a). Increasing heating temperature above eutectoid temperature makes austenite (γ) phase to exit, with cementite phase (Fe3C), silicon atoms available in the structure of cast iron make Carbene of cementite to change to graphite of Globular shape[5,6]. The globular graphite exhibits a polycrystalline structure, which is reason for ductility as graphite increase dislocation of atomic planes and its sliding. It is clearly observed in (Figure 4a, Figure 4b and c) for temperature over eutectoid (727°C) increasing of dimples and pores sizes, especially for over recrystallization temperature case (850°C), where the cone–cup fracture shape is obtained Figure 5. Very high temperatures can cause partial melting of segregation zones at the grain boundaries, which results in non-ductile fracture behavior (zero-ductility fracture).

Figure 2 also shows that increasing deformation velocity reduce strength and in the same time increase ductility (see Figure 3a, Figure 3b). Increasing of deformation rate makes the globular shape of graphite changes in the longitudinal direction for the oval shape [6]. Extra increase in the degree of plastic deformation is accompanied by even greater elongation of the shape of graphite inclusions in the direction of deformation, makes fast dislocation for atomic planes with temperature. Figure 6 shows 3-D plots illustrating relation between parameter of thermo mechanical treatment (temperature and deformation rate).

Table 2 compares material strength with temperature at different deformation rates, it is clearly appeared that strength decreases with increasing both temperature and deformation rates.

<table>
<thead>
<tr>
<th>Deformation rate (mm/min)</th>
<th>Temperature (°C)</th>
<th>Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room Temp.</td>
<td>450</td>
<td>750</td>
</tr>
<tr>
<td>1</td>
<td>870</td>
<td>710</td>
</tr>
<tr>
<td>5</td>
<td>739</td>
<td>571</td>
</tr>
<tr>
<td>25</td>
<td>525</td>
<td>380</td>
</tr>
</tbody>
</table>
Figure 2. Flow behaviors of Cast iron under thermo-mechanical treatment

Figure 3. Effect of thermo-mechanical treatment parameters on ductility

Figure 4. SEM examination of fracture plan illustrating ductile brittle transition
At the same time the ductility increase as clearly appeared in Table 3 as percentage elongation increases with temperature and deformation rates.

<table>
<thead>
<tr>
<th>Deformation rate (mm/min)</th>
<th>Temperature (°C)</th>
<th>% Elongation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Room Temp.</td>
<td>450</td>
</tr>
<tr>
<td>1</td>
<td>2.3</td>
<td>2.36</td>
</tr>
<tr>
<td>5</td>
<td>2.1</td>
<td>2.6</td>
</tr>
<tr>
<td>25</td>
<td>1.8</td>
<td>2.62</td>
</tr>
</tbody>
</table>

The strain hardening coefficient calculated using Holman’s law (1), illustrated in Table 4. It is shown that as the strength decreases with the temperature and deformation rates, the strain hardening coefficient (n) decreases, which is an indication to increasing of ductility [16].

\[
\sigma = k \varepsilon^n
\]  

\(\sigma\) = Stress, \(k\) = Constant, \(\varepsilon\) = Strain, \(n\) = Strain hardening coefficient

<table>
<thead>
<tr>
<th>Deformation rate (mm/min)</th>
<th>% strain hardening coeff.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Room Temp.</td>
</tr>
<tr>
<td>1</td>
<td>0.6</td>
</tr>
<tr>
<td>5</td>
<td>0.56</td>
</tr>
<tr>
<td>25</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Figure 7 shows relation between Holloman’s equation strain hardening coefficient (n) eqn. 1 and the working absolute temperature.

5. Conclusion

Thermo-mechanical treatment included the synchronized application of heat and a metalworking process to an alloy, in order to refine the microstructure and change its shape. Thermo-mechanical treatments technology is performed on cast iron tension specimen. The flow behavior of cast iron is enhanced in ductility to be like steel flow behavior. Con-cup shape fracture is
achieved for temperature over eutectoid (727°C). Many pores and dimples appear in the microstructure of fracture surfaces of specimen with increasing temperature. This technology increases range of application of cast iron in bulk forming process such as, extrusion, forging, and rolling. It can be concluded that mechanical properties depends largely upon the various form of heat treatment operations.

References