Effect of thickness and heat treatment on the toughness of AISI 1045 and AISI 6150 sheet steels

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ABSTRACT

Toughness is the combination of strength and flexibility, in the presence of elastic and plastic tensions. This quantity equals the surface area under the graph of stress-strain. Kahn standard sample is used for the comparison of toughness. The heat treatments of annealing and tempering were used for AISI 1045 samples; and annealing and austempering processes for AISA 6150 samples. To investigate the effect of thickness, 6 different thicknesses were used. In this study, the J parameter is used as a parameter to compare the toughness that is evaluated by the division of the surface area of Kahn sample F-X plot to its cross section.
Keywords*:* **Toughness, J parameter, Kahn standard sample**

1 Introduction

The fracture toughness is directly related to stress distribution on crack tip and thickness [1]. The effect of thickness is due to the transition of net plane stress to net plane strain [2]. Based on empirical investigations on fracture toughness curves, three different zones are visible [1-3]. These three specific zones are shown in figure 1. In zone I, the fracture toughness increases with increment of thickness. The net plane stress conditions establish in this zone, so fractional volume of material that absorbs the energy increases, and as a result the fracture toughness increases. The thickness of sheet is high in zone III and the net plane strain condition is dominant, thus the fracture toughness is independent of the thickness. The transition of plane stress to plane strain occurs in zone II. So the percent of plane strain increases with increment of thickness and consequently the toughness decreases [1-4].

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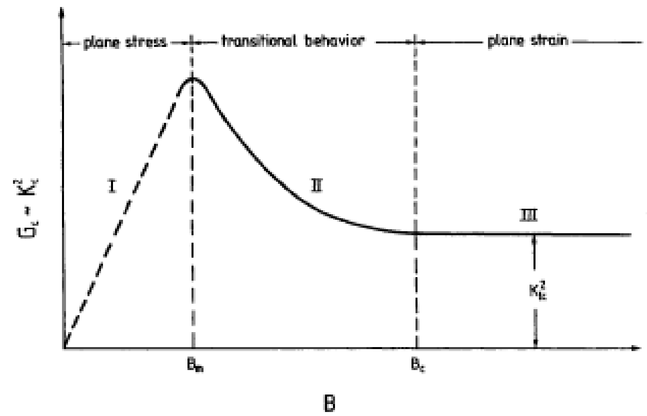

Figure 1: Effect of thickness on toughness [5].

One of the main methods for investigating the toughness is the J-integral. The J-integral is the energy release rate with crack growth and is a sign of toughness and evaluated by equation 1:

$$J(s) = \int_{\Gamma} \left(W\delta_{1j} - P_{ji} \frac{\partial u_i}{\partial X_1} \right) n_j d\Gamma - \int_{A_\Gamma} \frac{\partial}{\partial X_3} \left(P_{3i} \frac{\partial u_i}{\partial X_1} \right) dA \tag{1}$$

Where, J(S) stands for energy release rate with crack growth, Γ stands for the curve surrounding the crack, A_Γ stands for the surface that is defined by Γ, W stands for the strain energy density, T_i stands for the detailed vector of the contractile, U_i stands for the detailed vector of the displacement, P_{ji} stands for the detailed tensor of the tension. The J-integral is calculated counter-clockwise on the desired path. The J-integral is changed due to its 3-dimensional properties, so its average value is evaluated [6]. The measurement of J is done by Kahn sample according to ASTM B871-96 standard [7].

2 Experimental

In order to observe the effect of thickness and heat treatment on toughness, tensile test is done on different Kahn standard samples for AISI 1045 and 6150 steels. The chemical composition of steels is given in table 1. Sample that is used in this test has just a groove on one side and two holes at the ends for connecting to the jaw puller. The dimension of used standard sample is shown in figure 2. To complete the experiment, the sample is loaded until complete fracture.
According to papers, the results are dependent to the deformation rate and so, the deformation rate is 1.3 mm/min during the experiment. The schematic of sample and jaw puller are shown in figure 3.

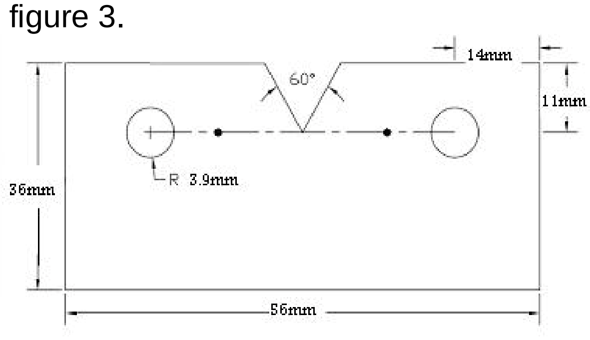

Figure 2: Dimensions of Kahn tensile standard sample [7].

Table1: Chemical composition of AISI 1045 and 6150 steel.

Element	Fe	C	Mn	Cr	Si	Ni	S	P
6150	Base	0.518	0.986	1.11	0.27	0.0023	0.0071	0.0162
1045	Base	0.421	0.557	0.131	0.313	0.108	0.0088	0.0156

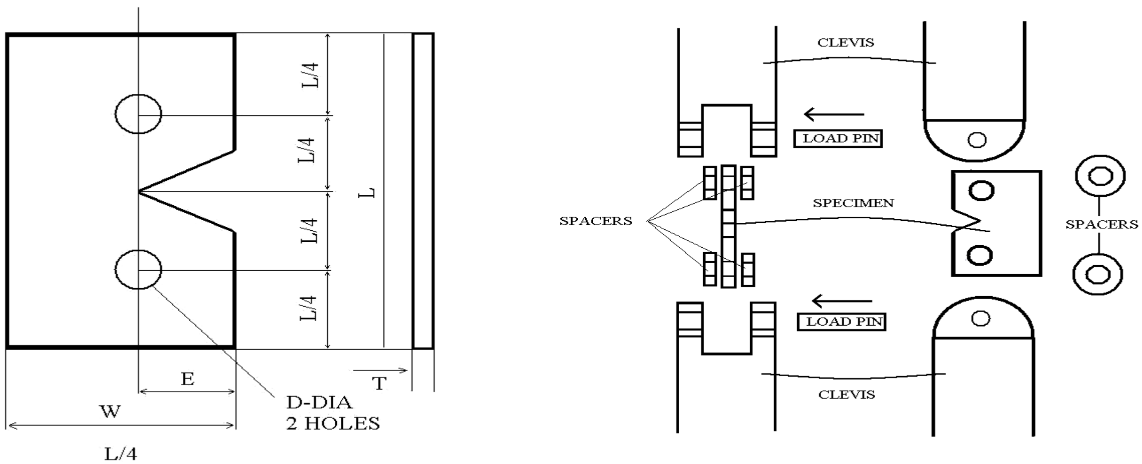

Figure 3: Schematic of sample and jaw puller [7].

To study the effect of heat treatment on toughness, two different heat treatment processes are done for each of two steels according to table 2. Homogenizing is done before tempering, annealing or austempering, for removing the dendritic structure and also non-uniform chemical composition.

Table2: Different done Heat treatment and their procedure.

Heat treatment	Procedure
Homogenizing	For both steels are Similar, the sample heats 20 min in 900^0C and then quenched in air.
1045 Annealing	The sample heats 20 min in 850^0C and then cooled down in furnace till 650^0C, then quenched in oil bath.
1045 Tempering	The sample heats 20 min in 850^0C and then quenched in oil. After quenching, the sample tempers 60 min in 540^0C and finally quenched in air.
6150 Annealing	The sample heats 20 min in 830^0C, then cooled down in furnace till 675^0C and kept in furnace for 120 min, then finally quenched in oil.
6150 Austempering	The sample heats 20 min in 870^0C, and then placed in 320^0C molten salt bath; the samples are kept in bath for 60 min and then quenched in air.

In order to investigate the effect of thickness, 6 different thicknesses is considered for each heat treated steels, so 24 tensile samples are prepared.

4 results and discussion

F-X plots are obtained with doing the tensile test on 24 samples. As it was complained, J-parameter is used for comparing the toughness that evaluated by dividing the surface area of F-X plots to cross section of sample. Table 3 is shown the values of J for all 24 samples. Also, figure 3 and figure 4 are shown the variations of J with thickness of 1045 and 6150 respectively.

Table 3: Types of heat treatment and thickness Kahn tensile sample and J-parameter values.

Steel types	Heat treatment	Thickness (mm)	J(Mpa.m)
AISI 1045	Annealing	0.5	0.522
		1	0.737
		1.5	0.857
		2	0.827
		2.5	0.815
		3	0.810
	Tempering	0.5	0.203
		1	0.842
		1.5	1.15
		2	0.897
		2.5	0.845
		3	0.837
AISI 6150	Annealing	1	0.950
		1.5	1.283
		2	1.459
		2.5	1.232
		3	1.211
		3.5	1.205
	Austempering	1	0.524
		1.5	0.712
		2	1.067
		2.5	0.821
		3	0.750
		3.5	0.714

According to figure 4, firstly in both annealed and tempered samples, the toughness increases with increment of thickness due to locating in plane stress zone. With increasing thickness to 1.5 mm this increase is observed and J maximum occurs in 1.5 mm, since then, due to the mixed zone toughness decreases. With increasing thickness to 2.5 mm, significant reduction in toughness due to the plane strain share is viewed, But the toughness decreases with increasing thickness of 3 mm is not so much because we get into the plane strain zone. The J_{1C} values for annealed and tempered samples are 0.810 and 0.835 Mpa.m respectively. Because of high flexibility of tempered sample

in comparison to annealed sample, its dependence to sample thickness is more than the annealed sample.
Different areas of plane stress, plane strain and mixed can be seen in figure 5 for both annealed and austempered samples. In both samples, the toughness is increased to 2mm thick (plane stress), from 2 to 2.5 the mixed condition is dominant in the area, and after 2.5 mm the J parameter is fixed and plane strain condition is dominant in the area. The toughness of annealed sample in all thicknesses is more than austempered sample. Although, the strength of austempered sample is greater than the sample annealing, but the flexibility of sample annealing is greater; and since the toughness is the combination of strength and flexibility, toughness of annealed sample is more.

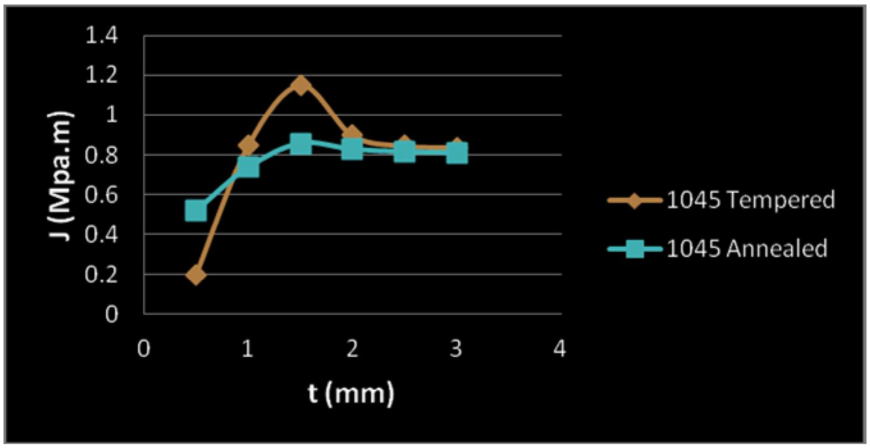

Figure 4: J-parameter value variations with thickness for 1045 steel (red) tempered (blue) annealed.

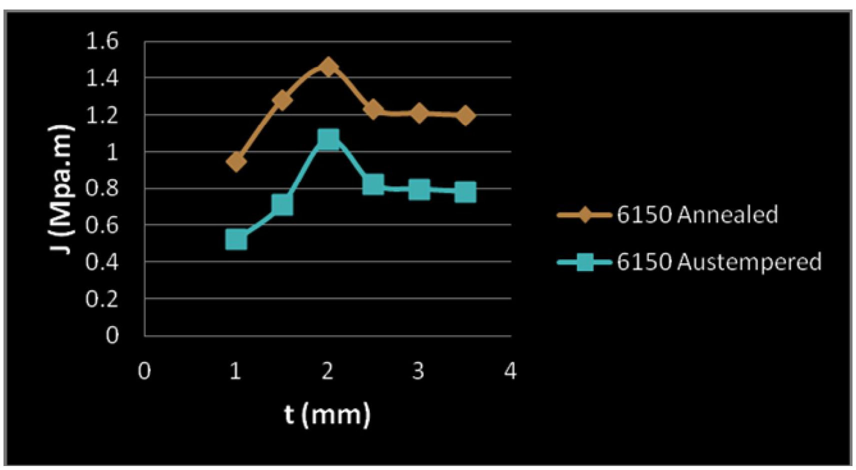

Figure 5: J-parameter value variations with thickness for 6150 steel (red) austempered (blue) annealed.

Comparison of two steels with two different heat treatments can be concluded that annealed 6150 steel has the highest toughness in all thicknesses (Figure 6). The presence of alloying elements such as chromium and vanadium activates strengthening mechanisms and secondly the structure is softened with annealing operation; and consequently the toughness is high. The lowest toughness is related to annealed 1045 sample; despite the low strength and high flexibility.

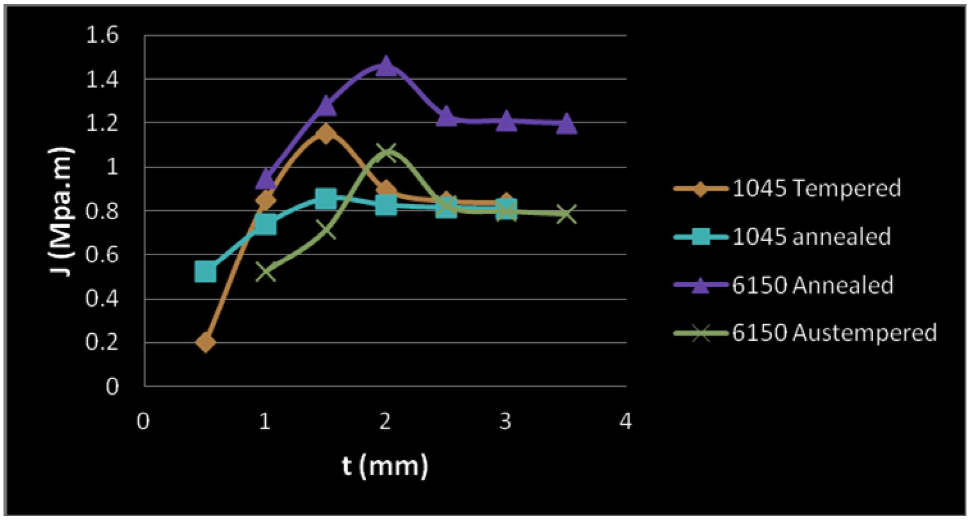

Figure 6: Comparison of toughness for 1045 and 6150 Steels.

5 Conclusions

1- The toughness increases with increasing thickness due to locating in plane stress zone, the toughness increases after entering into mixed zone. Toughness down continues to plane strain to reach a constant value of J_{1C}.

2- Heat treatment has a direct impact on toughness, due to changes in strength and flexibility, the toughness reduced or increased.

3- The flexibility of 1045 steel increases by doing annealing operation but due to low strength, the toughness is decreased. The toughness of tempered sample is greater than annealed sample because of its high strength.

4- Due to presence of strengthened elements like vanadium and chromium in 6150 steel, its strength is high and after annealing operation the flexibility increases; consequently the toughness is high.

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