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The Plastic Depth of Heat Treatment Steel Alloy (AISI 01) Due to Torsion Test

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Abstract: The torsion test is considered the best used when the part is subjected to static or dynamic torque. Many published research have investigated the torsion of non-heated metals. However, very few published research dealt with the plastic depth of heat treated metals. The aim of this research was to study the effect of heat treatment on the torsion behavior of steel alloy (AISI 01), which can be used for manufacturing small and medium drills, taps and reamers. The diameter of specimens used was 15 mm. The metal used was heat treated under different conditions, then torsionally tested. The results of torsion test were divided into two groups: results obtained during elastic limit from which the shear stress, shear strain and modulus of rigidity were calculated, while from the results obtained during plastic limit the plastic depth was calculated by applying derived equation when the angle of twist was more than yield value. The results obtained indicated that the value of hardness alone is not sufficient to establish heat treatment conditions. Rather, It was found that the determination of plastic depth together with hardness can help in the establishing of the optimum condition which was hardening temperature of 820°C, hardening time 20 min and tempering temperature 220°C. This condition produces hardness of 60 HRc and plastic depth of 2.5 mm.

Key words: Steel alloy (AISI 01), heat treatment, torsion test, plastic depth, hardness test

INTRODUCTION

Torsion test is mainly used for determination the modulus of rigidity of material. Also during this test the shear behavior of material during elastic and plastic limit can be studied.

It is well known that during torsion test the material deforms elastically until reaching yield point. During elastic limit the distribution of shear stress will be zero at the center and maximum at periphery. Also during this limit the shear stress is linearly proportional to shear strain (Fig. 1). While during plastic limit the material deforms plastically i.e. the relation between shear stress and shear strain becomes non-linear as indicated[1].

Because the torsion test specimen is not subjected to necking, as in tension, or barreling, as in compression, it is possible to carry the test to large plastic deformation. Hot torsion test had been conducted[2,3] on nickel-base alloy at constant shear strain rate. The results show that at low temperature 800°F the behavior was cold deformation, in which the torque increases continuously up to fracture, while at 1800°F, the behavior became hot working deformation. Moreover the plastic deformation starts from the peripheral toward the center of bar by increasing the angle of twist more than yield value. It is very useful to determine the relation between the deformed depth and angle of twist. This relation was derived and applied to determine the plastic depth for non-heat treated and heat treated specimens.

MATHEMATICAL CONSIDERATION OF TORSION BEHAVIOR DURING PLASTIC RANGE

During the translation from elastic to plastic behavior there is no change in equilibrium conditions, but there is a change in the relationship between shear stress and shear strain i.e. the relationship will change from linear to non-linear at yield point as shown in Fig. 1.

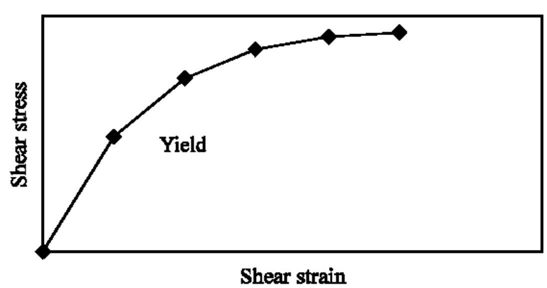

Fig. 1: Relation between shear stress and shear strain

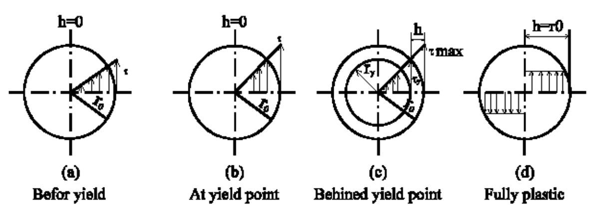

Fig. 2: Shear stress distribution

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To study the theoretical behaviors of torsion in plastic zone it is usually started to consider a plastic model which similar to elastic model[4] pointed out that when a round bar is twisted gradually until becomes fully plastic, the shear stress distribution can be described in four stages as shown in Fig. 2.

Figure 2a represents the stress distribution during elastic limit. While Fig. 2b represents the stress distribution when the bar behavior reaches the yield value. Beyond this value the bar starts to behave plastically when the twist angle is increased above yield value (Fig. 2c). With further increase of twist angle the amount of plastic deformation is increased until the section becomes fully plastic (Fig. 2d).

To derive the equation for calculation the depth of plastic zone h, consider firstly Fig. 2b, the value of the torque for developing this state is:

$$T_y = \frac{\tau_y . J}{r_0} \frac{\pi}{2} . \tau_y . r_0^3 , \text{by taking } J = (\pi/2) r_0^4 \quad (1)$$

$$\theta_y = \frac{T_y L}{G.J} = \frac{\tau_y . J.L}{r_0 . G.J} = \frac{\tau_y . L}{G.r_0} \quad (2)$$

where: τ_y = yield shear stress
T_y = yield torque
r_o = radius of bar
θ_y = yield angle of twist
L = bar length

Consider now Fig. 2c. it can be noted that the shear strain is still proportion with the radius r_0 even to the material whose strain is plastic. From Fig. 2:

$$h = r_o - r_y \text{ at } \theta > \theta_y \quad (3)$$

where, r_y = yield radius, from the elastic analysis of torsion at yield point

$$r_y = \gamma_y (L/\theta) = (r_o . \theta_y . L)/\theta . L = r_o (\theta_y/\theta), \quad (4)$$

where, γ_y = yield shear strain

By substituting the value of r_y in Eq. 3 the following is obtained:

$$h = r_o - r_o (\theta_y/\theta) = r_o (1 - \theta_y/\theta). \quad (5)$$

The distribution of shear stress continuous in r_y which is given by:

$$\tau = \tau_y (r/r_y) \text{ for } o < r < r_y \quad (6)$$
$$\text{or } \tau = \tau_y \text{ for } r_y < r < r_o$$

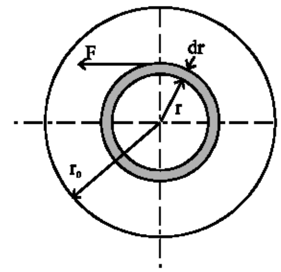

Fig. 3: Shear stress analysis

In order to derive the maximum value of torque in terms of yield torque[5] consider the static equilibrium for a section is equal to the resisting torque due to stress distribution to external torque as shown in Fig. 3.

$$T_{max} = \int_0^{r_0} 2 \pi . r \, dr. \tau . r \quad (7)$$

By using Fig. 2c this equation can be written in the following form:

$$T_{max} = \int_0^{r_0} 2\pi . r \, dr. [\tau y(r^2/r_y)] + \int_0^{r_0} 2\pi . r \, d_r . d_r (\tau_y)(r) \quad (8)$$

$$T_{max} = \frac{2\pi}{3} . \tau_y . r_o^3 [1 - 1/4 (r_y/r_o)^3] \quad (9)$$

By substituting the value of τ_y from Eq. 1 and the ratio r_y/r_0 from Eq. 4, in Eq. 9 it can be obtained:

$$T_{max} = \frac{4}{3} . T_y [1 - \frac{1}{4} (\theta_y/\theta)^3] \quad (10)$$

Equation 10 shows that the relationship between T and θ is non-linear.

$$T_{max} = (4/3) T_y = 1.33 T_y \text{ at } \theta = \infty \quad (11)$$

$$T_{max} = 1.32 T_y \text{ at } \theta = 3\theta_y \quad (12)$$

Experiment work and results: During this investigation number of specimens used were made of steel alloy (AISI 01) whose chemical composition is: 0.95% C, 1.1% Mn, 0.6% Cr, 0.6% W and 0.1% V[6]. In order to study the torsion behavior, the specimens for torsion test were prepared with scratched line as shown in Fig. 4.

This technique was used to show the amount of plastic deformation when the specimens were subjected to torsion test. The large twisting angle of scratched line means the large amount of plastic deformation as illustrated in Fig. 5. From Fig. 5, it can be noted that the scratched line is twisted around three rotations i.e. 1080°.

Table 1: The results of hardness and torsion test for non and heat treated specimens

		Hrc	T_y(N.m)	θ_y (degree)	τ_y (N/mm^2)	γ_y (mm/mm)	τ_{max} (N/mm^2)	G (N/mm^2)	h (mm)
Torsion test of non heat treated metal		20	280	65	422	0.056	706	7535	7.04
Heat treatment conditions									
Hardening time (20 min)	Hard temp. (°C)								
	790	55.0	470	5	709	0.0430	768	16488	2.81
Tempering temp (180°C)	820	62.5	880	37	1328	0.0320	1426	41500	1.71
	850	61.0	820	35	1237	0.0305	1469	40557	2.35
Hardening temp (820°C)	Hard time (min)								
	15	56.0	560	47	845	0.0409	901	20660	2.46
Tempering temp (180°C)	20	62.5	870	35	1312	0.0305	1500	43016	1.79
	25	63.0	760	33	1146	0.0280	1385	40928	1.60
Hardening temp (820°C)	Tempering temp. (°C)								
	180	62.5	870	35	1312	0.0305	1500	43016	1.79
Hardening time (20 min)	200	61.0	820	38	1237	0.0330	1389	37484	2.45
	220	60.0	810	40	1222	0.0340	1328	35941	2.50

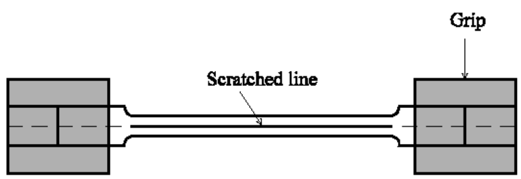

Fig. 4: Prepared specimen for torsion test

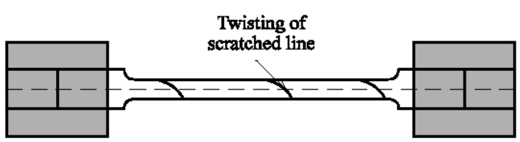

Fig. 5: Twisting of non-heat treated specimen (Large amount of plastic deformation)

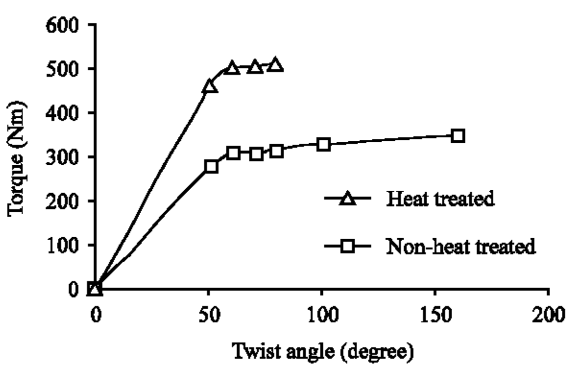

Fig. 6: Variation between θ and T

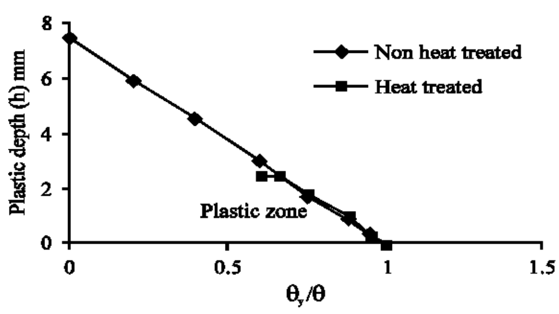

Fig. 7: Variation between h and (θ_y/θ)

Two specimens were non-heat treated and the rest heat treated under hardening temperature ranged from 790-820°C, heating period 15-20 min and tempering temperature 180-220°C. All the specimens were then torsionally tested. Figure 6 shows the results obtained from torsion test for both non-heat treated and heat treated specimens.

The maximum twist angle for non-heat treated specimen was 1080°, which is not shown in Fig. 6 for shortening. From these curves the yield torque Ty and the yield angle of twist θ_y were determined. From the elastic zone, θ_y,γ_y and modulus of rigidity G were calculated by using the following formulas:

$$\tau_y = \frac{16T}{\pi d^3},\ \gamma_y = \frac{\theta.r}{L} \text{ and } G = \frac{\tau}{\gamma}$$

From the plastic zone T_{max} and θ_{max} were determined. The results obtained from heat treatment and torsion test are summarized in Table 1.

In addition, the value of plastic depth was calculated by using Eq. 5 and given in Table 1. From this equation, it can be noted that the plastic depth h is inversely proportional with the ratio of θ_y/θ. The results of this proportion are shown in Fig. 7 from which it can be concluded that when $\theta = \theta_y$, (i.e. ratio of $\theta_y/\theta = 1$), h is equal to zero. As θ is increased more than θ_y, the plastic depth increased. When θ reaches infinity value the ratio becomes zero and h is equal to the radius of specimen. This means that the specimen is fully plastic. This curve is very useful for determining the value of plastic depth for any given value of θ more than the yield angle of twist for non-heat treated specimens. Similar curve was plotted for heat treated specimens, but the value of h was small because the metal was hard as shown in Fig. 7.

DISCUSSION

The torsion results obtained from testing non-heat treated specimens indicated that the torsion strength

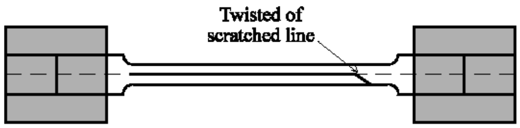

Fig. 8: Twisting of heat treated specimen (Small amount of plastic deformation)

during elastic limit was low comparing with the strength of heat treated specimens. However, the plastic depth was large around 7.07 mm during plastic zone because the total angle of twist was large. This means that the specimens deformed plastically in large amount when they were subjected to torsion load. On other hand the torsion results obtained from testing heat treated specimens indicated that the torsion strength was increased sharply while plastic depth decreased considerably since the angle of twist was very small. This can be supported by small twisting of scratched line as shown in Fig. 8.

From the results of hardness and torsion test, the shear stress is considered as an important property, which can be used in design and manufacture drill, tap and reamer because all these are subjected to torsion load in service. The usefulness of finding the value of τ_y is to calculate the yield torque for any given diameter and from which the power of machine can be computed by following equation when rotational speed of machine is known: Power = yield torque X angular velocity.

Furthermore the value of Tmax in Eq. 11 and 12 is approximately the same and can be calculated when T_y is known. This means that for heat treated metals the maximum torque can be calculated by determining T_y from torque-twist angle diagram because some times it is difficult to continue the twisting of hard metals more than yield value during torsion test to avoid slipping or damaging the grips of specimen.

The other important factor is the plastic depth, which can give the amount of plastic deformation. This is very useful for heat treated metal, which is always showing less plastic deformation. Thus the results presented in Table 1 indicate that the maximum value of h is 2.81 mm for hardness 55 HRc and minimum value is 1.6 mm for 61 HRc. From these it can be concluded that the value of h together with the value of hardness can help in the selection of the optimum heat treatment condition for steel alloy (AISI 01).

CONCLUSIONS

From the discussion and results shown in Table 1, the following can be concluded:

1. Increasing either hardening temperature or hardening time improves the hardness and torsion properties during elastic limit, while decreases the plastic depth during plastic limit.
2. Increasing tempering temperature decreases the hardness and torsion properties and consequently increases plastic depth.
3. The results obtained can be used in designing and manufacturing small and medium size of drills, taps and reamers, which will be made from steel alloy (AISI 01).
4. The optimum heat treatment condition is hardening temperature of 820°C, hardening time 20 min and tempering temperature 220°C which produce hardness of 60 Hrc, maximum shear stress of 1328 N mm^{-2}, modulus of rigidity of 35941 N mm^{-2} and plastic depth of 2.5 mm.

REFERENCES

1. Hibbeler, R.C., 1997. Mechanics of Materials. Hall Upper Saddle River, New Jersey, pp: 243.
2. Shapiro, E. and G.E. Dieter, 1970. Mechanical Metallurgy by George, E. Dieter (Ed.), 3rd Edn., 1986, McGraw Hill Book Co. Metall. Trans., 1: 1712.
3. Shapiro, E. and G.E. Dieter, 1971. Mechanical Metallurgy by George, E. Dieter (Ed.), 3rd Edn., 1986, McGraw Hill Book Co. Metall. Trans., 2: 1385-1391.
4. Popov, E.P., 1978. Mechanics of Materials, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 2nd Edn., pp: 71-73.
5. Nadia, A. ,1950. Theory of Flow and Fracture of Solids. 2nd Edn., Mc Graw-Hill Book Company, New York, 1: 347-349.
6. Anonymus, 1999. Arne Cold Work Tool Steel, 3rd Edn. Uddeholm Company, pp: 3-7.