Impact Strength Comparison with Carburization Case Depth Variation for Gear Steel by Instrumented Charpy, Izod and Brugger Tests

Anand Verma^{a,*}and Konchady Gopinath^b

^a MED, Technical Center, Ashok Leyland, Vellivoyalchavdi, Chennai, India

^b MDS, Mech. Engg. Dept., Indian Institute of Technology, Madras, India

Abstract: Impact strength of gear steel assist in estimating the sudden load bearing capacity of the steel. Traditional Charpy and Izod tests provide qualitative assessment of impact strength of steel. Brugger method is evaluated in this paper for case hardened steel. The instrumented impact test results are compared by all the methods for case hardened EN353 steel. The impact results are also compared by varying case depth to assess its influence on test methods. New co-relation is proposed for verification of Brugger impact strength. Fracture surface of impact specimens were characterized using SEM to analyze the associated failure modes and mechanisms. Compared to traditional methods, Brugger method found effective for quantitative impact strength determination of case hardened steels.

Keywords: Charpy test; Izod test; Brugger test.

1. Introduction

Gears subjected to impact load during operation were reported for premature failure due to tooth bending, shear or chipping [1]. Traditional standard Charpy and Izod methods were indirect, economic methods of quality control and surveillance in many industries [2-3]. There was no standardized process available for testing the toughness of case-hardened steel. Tikhonov and Palagin [4] evaluated impact strength of steel by special lobe ends specimen (cylindrical specimen having flat end at both ends and radius at transition) that replicates gear teeth, called as Brugger specimen. Diesburg and Eldis [5] reported that Brugger specimen was designed to resemble the root radius of an actual gear tooth and the angle of loading resembled that of experienced in operation. The specimen was mounted in the fixture so that pendulum striker hits the broad surface of the specimen flat end, at an angle of 30^{0} to the impact direction. The specimen is broken with a single impact from pendulum striker. A specimen can be tested twice, impacting individually at both the flat ends. The dynamic force at break of the specimen was the characteristic parameter for impact toughness. Comprehensive comparative impact studies by Brugger, Charpy and Izod methods for case hardened low carbon steel were reported in this paper. Influences of case depth variation on the test methods were also studied.

2. Steel characterisation

Accepted for Publication: March 3, 2011

^{*} Corresponding author; e-mail: <u>cengg@yahoo.com</u>

^{© 2011} Chaoyang University of Technology, ISSN 1727-2394

Ni-Cr-Mo alloyed, EN353 steel of BS 970 standard, commonly used for gear application was selected for this study. Chemical composition of EN353 steel was checked on Spectro GmbH make spectrometer. Steel chemistry and specification were reported in Table 1. Grain sizes of the steel were checked by comparative method of ASTM E112 standard, found to be ranging from ASTM number 5 to ASTM number 8. In order to assess the steel cleanliness, inclusion ratings were analysed as per ASTM E45 standard and reported in Table 2. Structural analysis of the annealed steel sample showed uniform distribution of lamellar pearlite and ferrite. All the above analyses were conducted using Leica make metallurgical microscope. Hardness checked on Zwick/Roell make micro hardness tester as per ASTM E10 standard, found 185 BHN.

Table 1	. Chemical	composition	of the	FN353	steel c	of BS970	standard
	• Onernicui	composition		L11000	51001 0		Stundulu

Elements, wt.	С	Si	Mn	S	Р	Cr	Мо	Ni
Spacification	0.2	0.35	0.5	0.05	0.05	0.75	0.08	1.0
specification	max	max	~1.0	max	max	~1.25	~0.15	~1.5
Observation	0.17	0.19	0.60	0.04	0.04	0.92	0.1	1.03

Table 2. Inclusion ratings of the EN353 steel as per ASTM E45 standar

dThickness classifications	A (Sulphides)	B (Aluminates)	C (Silicates)	D (Oxides)
Thin	1	0	1	0.5
Heavy	0	0	0	0

3. Case carburisation

Charpy, Izod and Brugger impact specimens were case hardened in a sealed quench furnace as per the cycles shown in Figure 1. Impact specimens were carburised to two case depths, 0.6mm-0.7mm (LCD) and 0.9mm-1.0 mm (HCD). Three specimens at each case depth for a test method were prepared to ensure the repeatability of the results. Specimens for a case depth were hardened in the same batch to avoid influence of hardening cycles on impact properties. Post carburisation, metallurgical characterisation of test specimens were reported in Table 3.

4. Impact strength results

EN353 steel forged bar was milled to make standard Charpy V notch and Izod V notch specimens as per ASTM E23 standard. Specimens were prepared in the rolling direction of the bar. Notch on the specimens were introduced by wire cutting method pre carburisation in order to obtain precise dimensions and reduce cutting stresses. Brugger specimens were prepared from the same steel bar. Impact tests were conducted on Zwick/Roell GmbH make instrumented pendulum impact tester (RKP 450). The impact load (column chart) and absorbed energy (line chart) results of Charpy, Izod and Brugger tests were com-Higher case depth (HCD) results pared. were reported in Figure 2 and lower case depth (LCD) results were reported in Figure 3.

Impact Strength Comparison with Carburization Case Depth Variation for gear Steel by Instrumented Charpy, Izod and Brugger Tests



Figure 1. Hardening and tempering cycles for impact specimen(Arrows ← → and ← → indicate hardening cycles to achieve case depth of 0.6mm-0.7mm (LCD) and 0.9mm-1.0 mm (HCD) respectively)

Table 3. Post carburisation metallurgical characterization of impact specimens

Darameters	Charpy specimen		Izod specimen		Brugger specimen	
1 arameters	HCD	LCD	HCD	LCD	HCD	LCD
Surface hardness(HV1)	712	718	715	705	709	667
ECD (mm) @ hardness drop to 600 HV1	0.96	0.66	0.94	0.68	0.89	0.62
Core Hardness (HV1)	452	436	444	440	418	407

Case micro structure

Tempered martensite with no carbide network

Core micro structure

Low carbon martensite







Figure 3. Fracture load and absorbed energy comparison by various test methods for LCD

5. Discussion

The impact studies showed significant variation of impact load and absorbed energy results with the test methods. Charpy and Izod impact test results found insensitive to case depth variation. The average absorbed energy observed by Charpy and Izod methods was around 3.5J for HCD and 3.2J for LCD respectively. However, Brugger method indicated absorbed energy around 35J for HCD and 16 for LCD. The average impact load for both HCD and LCD Izod and Charpy tests were around 10kN and 22kN respectively. The average impact load for HCD and LCD Brugger tests were around 58kN and 38kN respectively. Impact load determined by Charpy method was almost double of Izod method, irrespective of case depth variation. However, while reducing the case depth from 0.9 mm-1.0 mm to 0.6 mm - 0.7 mm, Brugger impact load reduced by almost six times, from 58kN to 38kN. As per Rogers and Plumtree hypothesis [6], in simply supported Charpy specimen and cantilever supported Izod specimen of same configuration, crack initiation takes place at the notch where stress is the maximum. When the specimen undergoes the maximum deflection (δ) and it fractures, the stress would have exceeded the strength. Hence, equating the simply supported and cantilever supported beam deflections, it is

16 Int. J. Appl. Sci. Eng., 2011. 9, 1

possible to get the relations between the impact loads in Charpy and Izod impact tests. Therefore,

$$\delta = \frac{P_c L^3}{48EI} = \frac{P_l l^3}{3EI} \tag{1}$$

where P_c and P_I are loads for crack initiation in Charpy and Izod modes, L is span between supports for Charpy specimen, 1 is distance between clamped notch and the point of impact for Izod specimen (2l = L), E and I are modulus of elasticity and moment of inertia respectively. Simplifying above equation gives,

$$P_c = 2P_I \tag{2}$$

Thereby, Charpy impact load results were almost twice that of Izod results.

Fracture toughness of EN353 steel was determined using Wilshaw, Rau and Tetelman [7] model applied to Charpy method,

$$K_{1c} = 2.9\sigma_{y} \left[\exp\left\{ \left(\frac{\sigma_{f}}{\sigma_{y}} \right) - 1 \right\} - 1 \right]^{\frac{1}{2}} \rho^{\frac{1}{2}}$$
(3)

Where K_{1c} is fracture toughness, σ_f is fracture

strength, σ_{y} is yield strength and ρ is specimen notch root radius. Substituting fracture stress (275 MPa) deduced from instrumented impact test results and yield strength for case carburised EN353 steel as 1270 MPa (UTS 1820 MPa) [8] to equation (3), fracture toughness is found to be 42.9 MPa \sqrt{m} . The calculated fracture toughness is within 7% range of reported fracture toughness for typical Ni-Cr-Mo alloyed steel [8], thereby validates the experimental impact results. A new co-relation is proposed for the theoretical evaluation of fracture toughness, using fracture stress 414MPa (fracture load divided by cross section area) deduced by Brugger method for the steel. Fracture toughness is found to be 45.77 MPa√m which is within 5% of fracture toughness reported for typical Ni-Cr-Mo alloyed steel [8].

$$K_{1c} = 2\sigma_{y} \left[\exp\left\{ \left(\frac{\sigma_{f}}{\sigma_{y}} \right) - 1 \right\} \right] \rho^{\frac{1}{2}}$$
(4)

Post impact test fracture surface of specimens were characterised under FEI Finland, make Quanta 200 Scanning electron microscope (SEM). Izod and Charpy specimens were fractured from notch end and Brugger specimens were fractured from radius end of flat fins. Charpy specimens revealed brittle fracture, with intergranular mode at surface (Figure 4a) and trans-granular mode (Figure 4b) at core as shown in Figure 4. Similar observations were made with Izod fracture specimens. Brugger specimens showed no such transition and fracture surface showed dimpled ductile failure (Figure 4c) at surface and significant plastic deformation (Figure 4d) at the core. Brugger specimens absorb higher energy during impact testing at a given case depth compared to that of Charpy and Izod specimens. This results in ductile failure for Brugger specimens and brittle failure for Charpy and Izod specimens.



Figure 4. SEM images of fractured Charpy and Brugger specimens. Charpy specimen: Brittle fracture, a) Surface, intergranular mode b) Core, transgranular mode Brugger specimen: Ductile fracture, c) Surface, dimpled fracture d) Core, significant plastic deformation

6. Conclusions

- a) Impact load for case hardened EN353 steel was almost twice for Charpy method compared to Izod method. However, absorbed energy in both the tests was nearly equal. Both Charpy and Izod methods found insensitive to variation of carburisation case depth.
- b) Impact load and absorbed energy by Brugger method were 58kN and 35J respectively, higher to traditional methods. Brugger method found sensitive to carburisation case depth, impact load and absorbed energy reduced to 38kN and 16J respectively with case depth reduction from HCD to LCD.
- c) Charpy and Izod method showed brittle failure with intergranular mode at surface

and transgranular mode at core. Brugger specimens showed ductile fracture with dimpled surface and significant yielding at core. The failure mechanism for various methods was not influenced by case depth variation.

d) Brugger test found effective for impact strength determination of case hardened steels. Established gear steel Brugger load can be considered as benchmark for development of alternative gear steel to avoid expensive and time consuming validations.

Acknowledgements

The authors are grateful to Dr. N. Saravanan, Special Director and Mr. Ravishankar, Assistant General Manager, Technical Centre, Ashok Leyland, India, for their technical support.

References

- [1] Davis, J. R. 2000. "Gear materials, properties and manufacture". USA: ASM International Publisher, 657-692.
- [2] Server, W. L. 2002. Instrumented Charpy test review and application to structural integrity, *Journal European Structural Integrity Society*, 30: 205-212.
- [3] Toth, L., Rossmanith, H. P., and Siewert, T. A. 2002. Historical background and development of the Charpy test, *Journal European Structural Integrity Society*, 30: 3-19.
- [4] Tikhonov, A. K. and Palagin, Y. M. 1994. Method of testing gear wheels in impact bending, *Technical Information, Metal Science and Heat Treatment*, 36, 12: 655-657.
- [5] Diesburg, D. E. and Eldis, G. T. 1978. Fracture resistance of various carburised steels, *Journal Metallurgical Transactions A*, 9: 1561-1567.
- [6] Rogers, M. G. and Plumtree, A. 1992. A comparison of Charpy and Izod test modes for polystyrene, *Journal Polymer*
- **18** Int. J. Appl. Sci. Eng., 2011. 9, 1

Testing, 11: 13-21.

- [7] Ritchie, R. O., Knott, J. F., and Rice, J. R. 1973. On the relationship between critical tensile stress and fracture toughness in mild steel, *Journal of the Mechanics and Physics of Solids*, 21: 395-410.
- [8] Raghavan, V. 2006. "*Physical Metallurgy Principles and Practice*". New Delhi: Prentice Hall Publisher, 150-152.