Shear Fracture and Industrial Overload Failure of Mechanical Fuse Shear Pin

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Abstract The science and engineering application of fracture is attractive and complex in nature. The notch provided shear pin geometry design for lower and known stress concentration factor engineered for premature shear pin fracture failure. The shear pin is one among type of mechanical fuse, safeguard bigger industrial rotary components by premature failure. The notch provided in shear pin act as reduced notch toughness where crack initiation and propagation starts from notch surface due to overload stress in the system. Advancement in technologically of mechanical fuses is one such key area, with which design of engineered microstructure analysis of shear failure discussed extensively. In the present investigation, shear pin failure were characterized to determine root cause analysis. Visual examination of fracture surface reveals pure ductile adiabatic shear fracture and metallographic examinations reveals non uniform size of spheroidal cementite carbide particles distributed uniformly slipping in coarse ferrite matrix plane of maximum shear stress causes the reason for shear fracture phenomena during crack propagation.

1. Introduction
The materials for static and rotary components design against engineering fracture and fatigue is industrially important from safety perspective [1] [9]. The role of fracture parameters like R curve, stress concentration factors, stress intensity factors, J integral, crack opening displacement (COD) and crack tip opening displacement (CTOD) were applied in evaluating calculation of damages under design loading geometry, crack length and crack propagation rate [3] [4] [6]. The application of engineering fracture at known stress concentration were applied for various mechanical fuses. Among various mechanical fuses the one such fuse is shear pin which protect internals of double pipe heat exchangers. The needle bearing eliminates wear after shear failure and wobble causes premature shear failure as entire mechanical system shown in figure1 [5]. The double pipe exchanger has rotating scraper blade bolted to shaft which rotates within design rotation per minute [5]. The load increases beyond design speed (in rpm) in shaft, subsequently scraper blade rotates in same speed of shaft. In that case shaft rotates at higher speed; the scraper blade in turns also rotates at higher speed. The semisolid material cools inside double pipe heat exchanger; the scraper blade scraps the semisolid...
material at design speed of shaft [5]. If shaft rotates at higher speed simultaneously scraper blade experiences restraint from semisolid materials which in turn damage the scraper blades. In order to avoid scraper blade failure and other wear failures of exchangers system, shear pin were inserted in shear pin sprocket of pin hub which fails prematurely if shaft rotate beyond design speed [5]. The premature shear pin failure isolates the scraper blade from damage [11]. As of material selection and characterization for shear pin, the ultimate shear strength of shear pin is nominally less than tensile strength of blade material [3]. The desirable microstructure of shear pin and its role in mechanical fusing to safeguard scraper blade is studied extensively [5] [10] [11]. In the present study shear pin made of water hardened tool steel W1 grade were examined and analyzed for shear phenomena [10] [11]. Although failure of shear pin observed after 300 hours as such shear pin have not any specified design life for failure and it may fails whenever experiences overload stress in the double pipe heat exchanger system. The shear pin designed against fail safe design philosophy [3] [4] [6]. The failed shear pins are replaceable which protects internals due to overloading [3]. Once shear pin fails, heat exchangers operation halts and next new shear pin would be inserted in pin sprocket immediately for plant outage [9]. Before installing, the shear pins were subjected to non-destructive dye penetrant examinations and dimensional verification [9].

2. Materials and Methods
The shear pin made of W1 grade tool steel and its chemical composition shown in table1 as per American Iron and Steel Institute (AISI) standards [1]. The American Iron and Steel Institute also specify density as 7.84 g per cubic centimetre and thermal conductivity specified as 48.3 W.m / K at 95 deg C [6]. The toughness specified in intermediate range and grain size at full hardness was high as per shepherd standard [1] [8]. The modulus of elasticity specified as 210 GPa at room temperature [6]. The impact energy not specified clearly as energy absorbed during notch bar charpy impact test is very small and it is difficult to correlate energy observed with service performance [1].

| Elements            | Composition% |
|---------------------|--------------|
| Carbon              | 0.7–1.5      |
| Manganese           | 0.10–0.40    |
| Silicon             | 0.10–0.40    |
| Chromium            | 0.15 max     |
| Nickel              | 0.20 max     |
| Molybdenum          | 0.10 max     |
| Tungsten            | 0.15 max     |
| Vanadium            | 0.10 max     |
| Copper              | 0.20 max     |
| Phosphorous         | 0.025 max    |
| Sulphur             | 0.025 max    |
The machinability of W1 grade tool steel is excellent and shear pin were machined to final dimension as shown in figure 2a [8].

3. Experimental procedure
The failed parts of shear pin were inspected visually and macroscopically [9] [10]. The failed part were subjected to photo documentation; samples collected for detailed metallographic studies by which samples prepared using Struers cutting, Buehler mounting and polishing machine, metallographic section analyzed using optical microscopy and MIC205 model diamond pyramid indenter used for measuring hardness [9]. The X-ray fluorescence (XRF) technique was used for analyzing shear pin chemical composition with minimum and maximum standard deviation of 0.01 & 0.03 respectively except carbon content which could not measured by XRF [9].

4. Results and Discussion
The visual observation of shear pin clearly reveals shear fracture and fracture surface is bright at notch location N especially designed for reduced notch toughness as shown in figure 2a & 2b. The cross sections were macroscopically observed with three distinct different regions as shown in figure 2b. Crack initiation at zone A visually shows bright appearance under light [1] [10]. The three regions are visible distinctly A-crack initiated bright appearance under severe load (plain strain region) [8]; B-rapid crack propagated by slant fracture radial lines and C-shear lip both reveals ductile appearance under light [1] [8] [12]. The initial crack is brittle in nature due to reduced notch toughness at zone A while load bearing capacity exceeds strength of material typically results in ductile shear failure as visible in radial fibrous line subsequently shear lip leads to final fracture at zone C [7]. The fibrous fracture surface edge exhibits crescent shaped C is called shear lip on same plane of fracture surface. Although fracture surface clearly reveals mixed percent cleavage and dimple appearance, initial brittle behaviour at notch further leads adiabatic ductile shear fracture [10] [11] [12] [13] [14]. The average material hardness is measured as 182 HV across surface and failed section of shear pin [1] [2] [7]. The hardness of failed portion was measured after metallographic studies [9]. The hardness of shear pin material shows uniform across entire shear pin surface and cross section, which also confirms shear pin material were homogenized in nature [9]. The dimension of shear pin shown in figure 2a with notch radius r = 0.01 inches. The lower diameter D=6.5 mm and higher diameter D=7 mm with d/D ratio of 0.92 and r/d ratio of 0.04 with stress concentration factor k = 1.25 [4] [6]. The shear pin exhibits magnetic in nature when tested by ferromagnetic experiments. The microstructure clearly reveals
The continuous ferrite matrix phase is lower strength and deformed easily along with spheroidal cementite particles and assist in shear failure [3]. The lower interfacial energy of spheroidal cementite particles drives shearing process during fracture in ductile ferrite matrix [4]. The spheroidal carbides or cementite particles may form from initial phases which may be from pearlite, bainite or martensite [1] [4]. During initial annealing, spheroidal carbides may nucleate and form in austenite phase structure between lower and upper critical temperature range of W1 grade tool steel [4]. While slow cooling the spheroidal cementite or carbide particles further formed, whereas austenite transform to ferrite matrix without forming pearlitic phases. The spheroidal cementite phases arrest the formation of pearlite with final spheroidal carbides in ferrite matrix [4] [6]. The spheroidal carbide phases are orthorhombic in nature and may be (Fe-Mn-Cr) carbides, whereas large carbides are hexagonal in nature may be (WC) tungsten carbide [8] [12]. The hypo-eutectic carbide plays major role in shear deformation and failure during overloading stress acting at notch [10] [12].
Figure 3a. Carbid particles reinforce the ferrite matrix phase shown at 500X magnification.

Figure 3b. Spheroidal carbides reinforce ferrite matrix shown at 500X magnification.

Figure 4a. Carbides found at both ferrite grain boundaries and grain interiors of 1000X magnification.

Figure 4b. Few carbide elongated needle like structure after failure in ferrite grain boundary shown at 1000X magnification.

Figure 5a. Localized shear fracture perpendicular to loading direction at 1000X magnification.

Figure 5b. Shear disorted dominant deformation of carbides at 1000X magnification.
Figure 6a. Hexagon shaped carbide reinforces ferrite matrix phase with absence of shear at 1000X magnification.

Figure 6b. Same as 6a with bright field hexagon carbide image phase contrast at 1000X magnification.

Figure 7a. Triangular shaped carbide reinforces ferrite matrix phase with absence of shear 1000X magnification.

Figure 7b. Same as 7a with bright field triangular carbide image phase contrast at 1000X magnification.

Figure 8a. Tetragonal oval shaped carbide reinforces the ferrite matrix phase with no shear deformation 1000X magnification.

Figure 8b. Needle like carbides found in grain interior ferrite phase after failure shown at 1000X magnification.
The spheroidal carbides reinforce with ferrite grain and grain interior as shown in figure 4a and spheroidal carbides elongated needle like structure due to overload deformation as shown in figure 4b. Once the applied shear stress reaches or exceeds shear stress of uniaxial tensile strength of W1 grade tool steel, spheroidal carbides dominantly deform by shear distortion as per maximum shear stress failure theory as shown in figure 5a & 5b. The carbides deformed in direction perpendicular to applied loading direction. The spheroidal cementite carbide nucleation were ensured before cooling from annealing temperature and during cooling process for further spheroidal cementite nucleation cum growth formation during shear pin heat treatment processing [8]. The pro-eutectoid spheroidal cementite may also be formed by spheroidizing treatment after water hardening with which initial spheroidal cementite phases formed from martensite phases [1][8][10].

The hexagonal, angular and oval carbide particle reinforced with ferritic matrix have not shown any influences adiabatic shear fracture as shown in figure 6, 7 & 8a [1] [2]. The carbide particles deforms needle like structure in grain interior due to stress distribution in matrix phase as shown in figure 8b. The coarser ferrite grain boundary reinforced by spherical carbides leads to fibrous ductile shear failure as shown in figure 9a & 9b [7] [13] [14]. The average ferrite grain size is 8.2µm and material shows coarse grain structure as shown in figure 9a. The sphere shape carbide particles of lower interfacial energy play a vital role in shear phenomena.

5. Conclusion

X-ray fluorescence, hardness and metallographic evaluation of shear pin concluded the failed shear pin is water hardened W1 tool steel. The carbon content may be 0.6 % C to 1.0 % C which could not obtain using X-ray fluorescence Spectroscopy. The shear pin designed to fail at notch with stress concentration factor of 1.25 when it experiencing overload stress is successful by optimum selection and design of favourable microstructures. The coarse ferrite grains have not influence shear fracture but distribute stress to carbide particles reinforced within matrix phase both at grain boundary and grain interior. The spheroidal cementite carbide particles originally influencing shearing fracture phenomena. Other than spheroidal carbides, geometric influenced triangular, oval, hexagonal carbides were not influence adiabatic shear fracture. The desired favourable microstructure of shear pin depends on final heat treatment practices which define size, shape, distribution and orientation of carbide particles. The adiabatic shear fracture based new material development shall be way forward in fail safe design philosophy.

Figure 9a. Coarse grain ferrite grain boundaries revealed at 1000X magnification.

Figure 9b. Non uniform spheroidal carbide particles size less than 1µm distributed uniformly at 1000X magnification.
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References

[1] Roberts G A and Gary R A 1980 Tool Steels American Society of Metals (USA; Material Information Society)

[2] Riedl et al, 1987 Developments in High Speed Tool Steels, Steel Research Volume 58 pp 339-52

[3] Todd S Gross, Micro-mechanisms of monotonic and cyclic crack growth American Society of Metals Volume 19 pp 105-13

[4] Tarsem J, Fatigue and Fracture Control of Weldments American Society of Metals Volume 19 pp 1077-79

[5] Heinz P Bloch and Claire Soares 1998 Process Plant Machinery Butterworth Heinemann Chapter 20 pp 693-95

[6] 2015 ASME Boiler and Pressure Vessel Code Rules for Construction of Pressure vessel Section VIII Division I, Non mandatory Appendix JJ (New York; ASME) 662-67

[7] Krauss G 1990 Steels, Heat treatment and Processing Principles American Society of Metals (USA; ASM International)

[8] Becherer B and Witheford T J, 1991 Introduction to Heat Treating of Tool Steels, American Society of Metals Volume 4 pp 711-25

[9] Chidambaram S and Ashok Kamaraj, 2017 Failure investigation of an industrial crankshaft made of ductile iron, Advances in Natural and Applied Sciences Volume 11 No.8 pp 25-30

[10] Minnaar K and Zhou M, 1998 An Analysis of the Dynamic Shear Failure Resistance of Structural Metals J.Mech. Phys. Solids Volume 46 No.46 pp 2155-70

[11] Gupta V, Argon A S and Cornie J A, 1989 Journal of Material Science Volume 24 No.6 pp 2031-40

[12] Woei-Shyan Lee, Chi-Feng Lin and Guo-Liang Xiea 1997 Dynamic shear deformation and failure behaviour of pure polycrystalline tungsten Materials Science and Engineering A Volume 247 pp 102-12

[13] Venugopal S, Venkadesan S, Mannan S L and Venugopal P 1992 A note on the predominance of dynamic strain ageing over the adiabatic shear deformation phenomenon in commercial purity titanium in compression tests at strain rates of 0.05 to 32 s-1 and temperatures of 303 to 573 K Journal of Materials Processing Technology Volume 30 pp 245-51

[14] Venugopal P, Venugopal S and Seetharaman V 1990 Some Aspects of the dependence of the flow curve of commercially pure titanium on the forming temperature and the strain rate Journal of Materials Processing Technology Volume 21 pp 201-17