American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN : 2320-0936
Volume-5, Issue-5, pp-74-79
www.ajer.org
Research Paper Open Access

Experimental investigations of hexagonal crimping die failure

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ABSTRACT: *This paper deals with the hexagonal crimping die failure of high carbon high chromium steel material. The failure modes were initially revealed and identified by the visual examination. Then the chemical analysis and metallographic examination havebeen carried at different positions of the failure die surface using scanning electron microscope (SEM). The microstructure evaluation reveals that failure occurs due to undissolved austenitic structure resulting in improper transition duringheat treatment.*

Key words:*Die, metallographic examination, heat treatment, chemical analysis, microstructure, high carbon high chromium steel.*

I. INTRODUCTION

The crimping is the process of folding or forming the metal into desired shape. In case of motorcar steering system, a hexagonal shaped crimping die were used to join ball tube and ball bin assembly.During this process the threaded portion of the ball bin is inserted into the ball tube and is held in the die cavity.Then, 32 ton of load is applied over the ball tube using pressing machine. This results in material flow of the ball tube into the threaded portion of the ball bin resulting in a rigid joint.

The die was made of high carbon high chromium steel (HcHcr), which was more commonly used in similar type of tools. The desired life cycle of this tool is expected to be one lakh cycle. But, in practice the die used to fail in low cycles (29646 cycles) only. This type of failures in case of automotive industries is a serious concern due to cost consideration in manufacturing and production. In this research article the effort has been made for probable cause of failure using failure analysis techniques,which helps to understand the causes of failurein order to extend the life cycle of the die.

In this context, alanemeet., al [1] has showed that, the short service life of the indigenous die component occurs due to incorrect heat treatment during cold working process. Also, occasional misalignment of the upper die teeth of the mould and lower die plate due to over exertion of the machine contributes to failure of the die material.Papageorgiouet., al [2] demonstrated using fatigue-corrosion cracking mechanism,the design deficiency and improper cooling conditions which lead to damage of the die after half of its predicted service life. Podgrajseket., al [3] has studied the die insert protected with diffusion layer and PVD coating. The metallographic examination at some critical region of the die inserts showed, significant spalling in the surface layer and the underlying diffusion layer.

The chemical analysis of the AISI D2 tool steel material was analyzed using an EDX spectrometer by Statharaset. al [4]. They showed the deficiency in design concerning, shape and mechanical properties are the principal causes that led to the premature failure of the die. Songet., al [5] investigated the microstructure and hardness of AISI D3 tool steel material. They showed that the microstructure of the hardened layer consists of martensite and retained austenite, while the transition between these two layers consists of tempered sorbite.

II. BACKROUND INFROMATION

The crimping dies are made of AISI D3 grade tool steel material, which exhibits excellent abrasion, wear resistance, good dimensional stability and high compressive strengthwas purchased from a steel supplier in heat treated condition and machined as per the service requirement. In order to use this die in satisfactory working condition, die material must meet the required chemical specifications and the hardness must be 45-55 HRC. The properties of materialare dependent on the microstructure, composition and the heat treatment. The microstructure of steel is composed of tempered martensitic matrix with various alloying elements (carbide precipitate) distributed within. These carbides are composed of molybdenum, chromium and iron and the size of the carbides varies for each alloying element. The molybdenum and chromium carbides tend to be larger in size and grouped together. The size of the carbides plays a key role in propagation of crack and fracture.

The ball bin as shown in Fig.1 is made of EN18D material which is widely used in industry and other applications because of their high tensile strengthand high hardness value (230-330 BHN)andits alloy composition isshown in Table 1.

The ball tube as shown in Fig. 2 is made of IS-3074CEW material having low carbon content, highly malleable and suitable for bending and widely used in automobile industry and the alloy composition isshown inTable 2.

III. EXPERIMENTAL METHOD

3.1 Visual examination:

The failed die surfaces were examined using visual inspection. The failed die surfaces revealed surface deformation and crack growth. The possible causes of this are due to alternate stress variation in the hexagonal corner.There is no evident for the cross sectional deformation in the die.

3.2 Hardness:

After the visual examination, in order to analyze the failure of die, the hardness readings were taken on a different area using Rockwell hardness tester.

3.3 Chemical analysis

To determine the alloy composition of the AISI D3 tool steel material is as per the manufacturer's requirement, the failed die sections were sent to PSG laboratory (Coimbatore, India) for chemical analysis.Optical emission spectrometry (OES) was used to determine the alloy composition of material.

3.4 Fracture Surface Analysis (SEM)

The samples were cut by electrical discharge machining using(SODIACK A320D-AWT) wire cut machine. The three samples were taken from the failed parts, at the hexagonal corner, middle portion and bottom portion of the die. The fracture surfacesamples were first ultrasonically cleaned andsurface examination were carried out by SEM (JEOL, Japan-JSM 6360).

IV. STRESS CALCULATIONS

4.1 Abbreviation

Z= Section modulus (mm^3)
σ_{mb}= Mean bending stress (MPa)
σ_{ab} = Amplitude bending stress(MPa)
$\sigma_{-1=}$ Endurance limit
K_f = Stress concentration factor
σ_y = Yield strength of material (MPa)
σ_u= Ultimate strength(MPa)
σ = Combined stress (MPa)
q = Notch sensitivity factor

Varying load:

Minimum load = 18 tons = 176580 N.
Maximum load = 32 tons = 313920 N.
Bending moment = Load x distance N-mm. (1)
Minimum bending moment: 4502790 N-mm.
Maximum bending moment: 8004960 N-mm.

$$Z = \left(\frac{\pi}{32}\right) D^3 = 402.12\ mm^3. \quad (2)$$

(σ_{mb}) = (Mean bending moment /Section modulus) = 15552.14MPa. (3)
(σ_{ab}) = (Amplitude bending moment / Section modulus) = 4354.6 MPa. (4)

$$K_f = 1 + q(K_t - 1) = 1.27. \quad (5)$$

(σ_{-1}) = 0.5 x σ_u
(σ_y) = 520 MPa.
(σ_u) = 900 MPa.

$$\sigma = \frac{(\sigma_{mb} + K_f)\times(\sigma_{ab}\times\sigma_y)}{\sigma_{-1}} = = 2.19 \times 10^4 \text{ MPa.} \quad (6)$$

Young's modulus of the die material (HcHcr) = 2.144 x 10^2GPa

V. FIGURES AND TABLES

Table 1 Material composition of EN18D

Element	C	Si	Mn	P	S
(Mass %)	0.39	0.33	0.9	0.05	0.05

Table 2 Material composition of IS–3074CEW

Element	C	Mn	P	S
(Mass %)	0.25	0.2	0.04	0.04

Table 3 Material composition of HcHcr

Element	C	Si	Mn	P	S	Cr	Ni	Mo	Cu	Fe
(Mass %)	2.28	0.736	0.299	0.042	0.0255	11.97	0.105	0.027	0.069	84.5

Table 4 Rockwell hardness test results

Position	Test 1(HRC)	Test 2(HRC)	Test 3(HRC)	Average
Right corner	52	54	54	53.33
Hexagon	53	53	54	53.34
Cracked zone	54	54	53	53.66
Width	54	54	54	54
Small piece	50	52	54	52

Fig. 1: Ball bin

Fig. 2: Ball tube

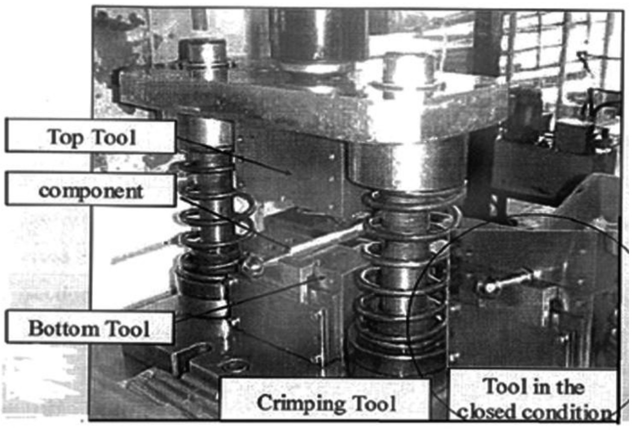

Fig. 3: Experimental setup

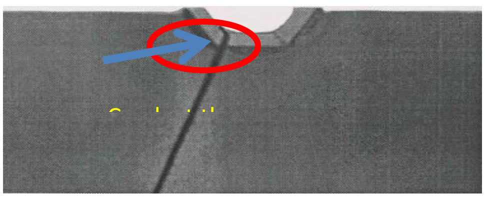

Fig. 4: Crack propagation on the hexagonal corner of die

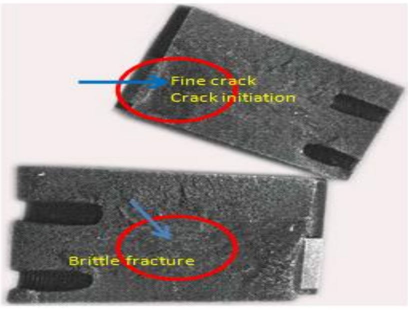

Fig. 5: Two broken pieces of die

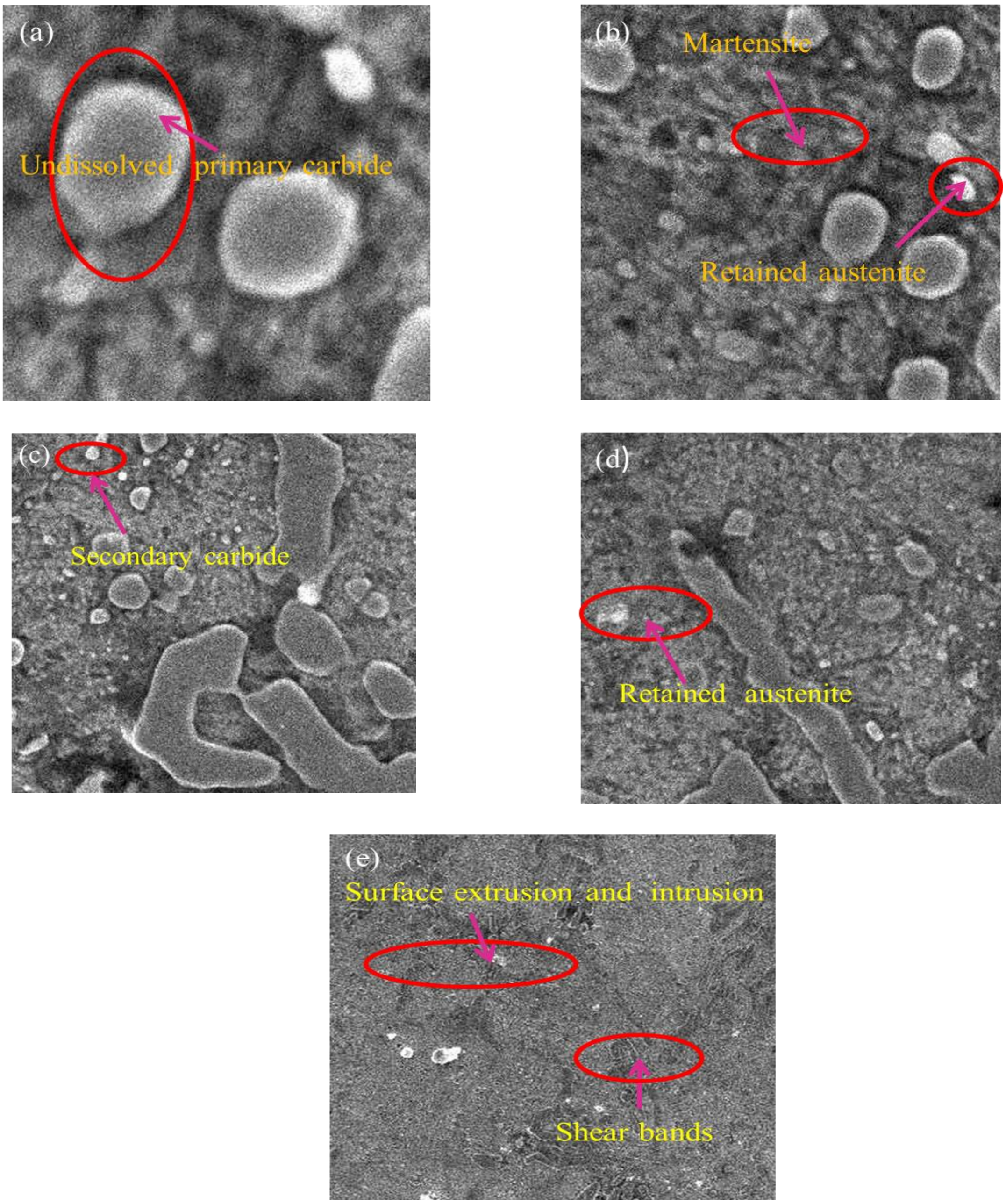

Fig. 6.characteristization of phases and defects in AISI D3 die material.
(a) Undissolved primary carbide (b) Martensite and retained austenite (c) Secondary carbide (d) Retained austenite (e) Shear bands

VI. RESULTS AND DISCUSSIONS

The hexagonal crimping die failure mode, which is used to connect ball bin and ball tube were carried out initially by visual inspection of the failed die. The surface of the die reveals crack at the hexagonal corner and it is propagating inward at the bottom of the die as shown in Fig.4. This occurs due to contact pressure between the hexagonal crimping die and the ball bin and ball tube during operation [6]. This initial crack after continuous usage of the crimping die has progressed to the surface and the failure of the die into two pieces has taken place, which is shown in Fig.5.

The cyclic applied load varies from 18 tons to 32 tons in the die during crimping operation. Hence, the bending stress developed in the die varied from 15552.144 MPa to 4354.6 MPaas shown in Equation 3 and 4 and the respective combined stress developed in the die was 2.194 x 10^4 MPa and young's modulus of the die material is 2.144 x 10^2GPa. This shows that the combined stress developed in the crimping die is closer to the young's modulus of the die material. From this it can be concluded that the design stress developed in the die is within the allowable limit.

Even though the combined stress developed in the die was within the allowable limit, the applied load was varying at each and every cycle tries to push the side surfaces due to ball tube expansion; this in turnleads to different stress concentration in the hexagonal corners and surfacesof the die. This continuous fluctuating stress at every cycle has led to the formation of fine cracks at the hexagonal corner and after some cycles of application has propagated inward into the die.

In cold working die operation the designers die design is to essential understand the fatigue failure and fatigue behavior of the die due to high loads and cyclic loading [7]. The primary source of failure taking place in cold working die operation is the adhesive wear due to the cyclic variation of the load during crimping operation [8].The visual observation of the cracks shows that failure of the crimping die has taken place due to the fatigue loading. The critical examination (crimping die)using scanning electron microscope shows that the failure has occurred due to higher stress concentration leading to fine crack growth, beach marks and shear bands [9].

In order to ensure the properties of material is as per AISI D3 tool steel alloy standard. The failure die tool steel was tested using OES and it was found that it satisfy the AISI D3 HcHcr tool steel. The composition of the material after testing is shown in table 3. In order to study the macro indentation, hardness measurements were carried using Rockwell hardness testing machine. These hardness measurements were done at right corner, hexagonal corner, cracked zone and width and it was found that the hardness was within the allowable limit (50-55 HRC). These data's are tabulated and is as shown in table 4.

A sample of the failed region is prepared for micro structural analysis using standard metallographic procedure. The fracture surfaces were washed with methanol and dried with dry air and the samples were etched with Nital 2% [10].In order to get a clear picture of the damage, fracture surfaces were observed using scanning electron microscope. Clear optimum images were observed in samples using 15 KV and low voltage mode to determine the depth sensitivity.

The microstructure of various portion of the specimen of D3 steel is shown in Figures.6(a) to Fig.6(e). Fig. 6(a) and 6(b) shows the microstructure composed of undissolved large primary carbide, tempered martensite and retained austenite [11].Martensitic structure is always associated with the percentage of carbon of the parent austenite phase; it may form either low carbon or high carbon martensite phase. Low carbon martensitic phase exhibits high toughness, ductility but having low strength. Similarly, high carbon martensitic structure exhibits higher strength but having brittle and non-ductile [10, 11]. From table 3 it is observed the percentage of carbon in HcHcr is 2.28. From this it can be concluded, that the HcHcr exhibits higher strength and having brittle and non-ductile. Also, it is known that increase of carbon content of austenite leads to decrease in martensitic start temperature and martensitic finish temperature [11, 12]. This in turn leads to difficulty in converting austenite to martensite. The probably causes of this can be seen in Fig.6(a) with undissolved carbide in the martensitic structure. This undissolved carbide phase is not desired, caused earlier failure of the die within the allowable cycle.

The Fig.6(c) shows that primary and secondary carbides and also the carbides were very coarse and inhomogeneous [5, 10].From Fig.6(e) it is observed a narrow zone of intense shear strain developed caused due to severe deformation (Shear band). Also, visible lines were observed on the surface that shows residue of the material extruded and has stuck to the die creating embossed lines (surface extrusion and intrusion). From this it is evident that sudden brittle failure has occurred without any material deformation. From this it is observed that improper cooling rate has caused undissolved carbides and retained austenite phase in the material.This undissolved carbide has led to increase in stress concentration and induced failure of the die.

VII. CONCLUSIONS

This failure investigation revealed that the AISI D3 material chemical composition and hardness of the material were within the acceptable limit. The metallographic examination of the fracture surface by scanning electron microscopy shows that the fracture occurs due to undissolved primary carbide, coarse carbide present in the martensite structure resulting in reduction of material strength. The combined stress developed in the die was verynearer to the yield strength of the material, whichleads to higher stress concentration on the hexagonal sharp corner due to cyclic load variation. This shows that the probable failure occur due to fatigue.From this it can be concluded that the design changes in the sharp corner of die and proper heat treatment and slow cooling method improve the martensite structure of material. This gives greatest life cycles to the die.

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