Research Article

D.D.D.P. Tjahjana, Y. Waloyo, and Triyono*

Failure Analysis of Super Hard End Mill HSS-Co.

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Abstract: The failure of tools will make a large impact to the productivity, so it must be investigated to avoid the next failure. In this case, the super hard end mill HSS-Co list 4SE code 6210 was broken when it was used for side milling processing of mild steel AISI A36 with rotation speed, cutting speed and cutting depth of 540 rpm, 0.10 m/min (4 ipm) and 16 mm respectively. Standard procedure of failure analysis was performed including macro-micro investigation using Scanning Electron Microscopy (SEM) with energy-dispersive spectrometry (EDS) attachment, micro hardness test, and Finite Element Methods (FEM) simulation. The results of failure analysis showed that fracture occurred due to stress concentration and micro defects of the super hard end mill. Two parts of fracture surface, rough and fine surface were found. Based on SEM-EDS investigation, it was known that the content of tungsten (W) and cobalt (Co) elements on the rough and fine surface was inhomogeneous. Excessive Co and W elements appeared on the fine surface while they disappeared on the rough surface. Excessive Co will diffuse with tungsten and carbon and lead to the separation of tungsten and carbon elements, so it greatly destroyed the alloys and lead to form the non-stoichiometry carbide points. Hence, the defective manufacturing processes which made the elements distribute inhomogeneous is concluded as the reason of the super hard end mill failure.

Keywords: failure analysis, super hard end mill, finite element method, cobalt

1 Introduction

Modern manufacturing industry prioritizes rapid and low-cost manufacturing process as well as high quality products. The United Nation Industrial Development Organization (UNIDO) through the quarterly World Manufacturing Production report has stated that world manufacturing output increased by 2.8 percent in 2016 [1]. Various machine components are produced by machining process, such as turning, milling, planner, and drilling. Miscellaneous spare parts and components in various fields, such as aeronautics, automotive, biomedical, and electronics are manufactured with the right finishing for precision and the proper functioning of the product. Based on this reason, high quality cutting tools must be applied for manufacturing processes.

HSS-Co is one type of the high-speed steel which has ability to machine material at high temperature due to high speed of cutting. The hardness of this materials can be maintained high (around 65 HRC) at high temperatures and called hot hardness. This hot hardness properties are obtained by modifying the microstructure through the addition of the carbide-former element such as Mo, W, V, and Cr [2]. Presence of cobalt (Co) element in HSS material increases the melting point of materials so it will maintain the hot hardness. Hardening temperature for HSS-Co can be 14 to 28°C higher than would be normal for similar grade without cobalt [3]. Unfortunately, cobalt additions slightly increase the brittleness of HSS. Excessive addition of cobalt can lead to the dislodging of carbide which is deleterious to the hardness and wear-resistance of tool [4, 5].

Failure on cutting tools will deteriorate the productivity of manufacturing processes. It will lead the wasting time, defect products and increasing of machining cost [6]. It is affected by several parameters, such as cutting speed, feeding and cooling [7]. A lot of studies have been subjected to improve the performance and life time of cutting tools. They were based on the finite element method [8], the statistical technique [9], and the cooling system [10, 11]. Moreover, the failure analysis for investigating the root cause of cutting tool failure on the manufacturing industries have been conducted by previous studies. A few of them are investigation of tungsten carbide end mill damage on the titanium alloy machining [6], analysis of bolt failure on the pipe connections of oil industry [12], three axial frequency for detection the failure of the twist drill [13], failure analysis of bolted joint caused by the effect of initial torque loading [14] and fracture in-
vestigation on the chisel holder arbor due to the presence of stress concentration [15].

Although there were a few previous studies which investigated the failure of tools, but the investigation of the failed of HSS end mill was limited. Moreover, there was uniqueness including the root cause and the failure mechanism in each failure case. Therefore, the aim of this study is to find out the failure cause of HSS-Co end mill. In this case, the failure occurred when cutting tool of super hard end mill list 4SE code 6210 was used for roughing process of side milling. End mill was mounted on the milling machine with power of 1.5 kW. The spindle rotation and feeding rate were 500 rpm and of 4 ipm respectively. The work piece material was low carbon steel A36 with a size of 50 mm × 50 mm × 300 mm.

2 Experimental

The investigated material in the case of failure was end mill cutter HSS-Co. Its specification is shown in Table 1 while the chemical composition is shown in Table 2 [16]. Initial observation was performed by collecting information at the time when the tools were used and failed.

Failure analysis of the end mill HSS-Co was performed in three stages. These stages was carried out based on previous research in failure analysis and failure analysis procedure. Nishida [17] recommended that great care should be taken not to damage the fracture surface during rust removal because there is usually only one fracture surface to be investigated.

The first stage was visual observation, in which it was performed by taking a picture under the digital camera and Scanning Electron Microscope (TESCAN Vega3 LMU) with EDX (OXFORD INCA Energy 250) attached. The macro and micro scale of surface fracture were revealed to find the initial fracture. The second stage was laboratory testing covering testing of micro Vickers hardness and the chemical composition analysis with energy-dispersive spectrometry (EDS) testing. The results of chemical composition testing were used to compare the chemical composition produced by producer and specifications issued by international standardization agency. EDS analysis was also performed in the same model of used end mill for comparison. Evaluation points in the used end mill were adapted to those in fractured end mill. Figure 1 shows the points of investigation in the failure end mill and the used end mill cutter HSS-Co. The selected surfaces of end mill were cross-sectioned with abrasive wheel using high flow coolant to maintain the low temperature during cutting processes. The last stage was stress analysis using the finite element method with SolidWorks software simulation. Simulation testing was conducted to determine the stress concentration at end mill. Based on the results of three stages, the failure analysis of the end mill HSS-Co was performed in comprehensive to determine the initial cracks and root causes of the fractured cutting tool.

![Figure 1: The points of investigation in (a) used end mill, (b) fractured end mill](image)

3 Results and Discussions

End mill HSS-Co was broken when it was used for the side milling process of steel A36 with a size of 50 mm × 50 mm × 300 mm. The fracture was in the middle part between cutter and shank as shown in Figure 1. Based on the initial observation, it was ensured that machine operation was in accordance with standard procedure and operator was experienced in operating the milling machines. The spindle rotation and feeding rate were lower than the maximum level as mentioned in Table 1. It was able to be concluded that the human error was negligible.

Surface appearance of the fractured end mill is illustrated in Figure 2. It is clearly seen that there are two very different parts in fracture surface section. The one-third part of fractured end mill surface is rough surface with several dimples, while the two-third part of that is fine and shiny surface. Beside different in surface texture, both surface sections are different in chemical composition. Figure 3(d) and (e) show the EDS spectra of the rough and fine surface. From the EDS spectra, it can be seen that there was clear difference in tungsten (W) and cobalt (Co) content between fine and rough surfaces. In fine surface, it was found that W and Co contents were 6.5% and 5.4% respectively, while there was no presence of both elements in rough sur-
Table 1: Specification super hard end mill four flute list 6210 code 4SE

| Dia. Of Mill Dia. of Cut | Shank Dia. | Length | Overall Length | rpm | Feed (ipm) | Density kg/m³ | Yield Strength MPa | Tensile Strength MPa | Elastic Modulus GPa | Poison Ratio |
|-------------------------|------------|--------|---------------|-----|------------|---------------|-------------------|-------------------|-------------------|-------------|
| 16                      | 16         | 50     | 95            | 640 | 5.1        | 8,180         | 3,250             | 3,800             | 210               | 0.28         |

Table 2: Chemical Composition end mill cutter HSS-Co.

| Classification | Steel Type Symbol | Chemical Component (%wt) |
|----------------|-------------------|--------------------------|
| High Speed Steel (HSS) | SKH57, M36, HS93R | C 0.9, Mo 5.5, W 6.5, Cr 4, V 1.8, Co 7.75 – 8.75 |

Furthermore, the content of the other carbide former elements such as vanadium (V) and molybdenum (Mo) in fine surface was higher than that in rough surface. The content of V and Mo in fine surface was 1.6% and 4.3% respectively, while it was only 0.6% and 1.2% respectively in rough surface. It means that alloying elements were not evenly distributed in all parts of end mill. To support these data, EDS analysis at the surface adjacent to fracture surface was also conducted and the EDS spectra on the 4 investigation points can be seen in Figure 4. It shows that 2 EDS points were lack of carbide-forming elements and the other points were excess carbide-forming elements. Figure 4(c), the EDS spectra of point 1 shows that the content of W, V, Cr, Mo, and Co were very low. The EDS spectra of point 2 (Figure 4(b)) shows that the chemical composition was almost similar to point 1 but Co content was higher. Figure 4(d) and 4(e) show that the content of W, V, Cr, Mo, and Co were very high even exceeding the standard.

It is well-known that the rough surface of fracture shows the ductile fracture while the fine surface shows the brittle fracture. Ductile and brittle fractures are also characterized by intergranular and transgranular cleavage as seen in Figure 5. Based on the standard chemical composition, super hard end mill four flute list 6210 code 4SE is classified in M series of high speed steel (HSS) where molybdenum (Mo) is the one of primary alloying elements. It contains 3.5 to 10% Mo approximately. It also contains the other alloying elements such as vanadium (V), tungsten (W), chromium (Cr) and Cobalt (Co). Mo and W are strong carbide former in which they can substitute its role each other. V and Cr are also strong carbide former and refine the primary grain. Cobalt is not carbides former. It inhibits grain growth at elevated temperatures and improves substantially retention of hardness and high temperature strength [18]. The carbides are very hard and significantly contribute to wear resistance and hot hardness.
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Figure 3: The difference of the chemical composition between the fine and the rough surface (a) macro view, (b) rough surface, (c) fine surface, (d) EDS of rough surface, (e) EDS of fine surface

Figure 4: EDS analysis at the surface adjacent to fracture surface (a) points EDS, (b) EDS spectra of point 2, (c) EDS spectra of point 1, (d) EDS spectra of point 3, (e) EDS spectra of point 4

Figure 5: The boundary area between the fine and the rough surface (a) macro view, (b) detailed view, (c) crack, (d) EDS of crack area

Figure 6: The initial crack exposure (a) crack growth direction (b) macro view of initial crack, (c) detailed view of initial crack, (d) visible carbide, (e) EDS of carbide

at high temperature) [19]. In the rough surface, there was no presence of W and low content of Mo (1.2%) and V (0.6%). The formed carbide will be low if the content of carbide former elements is low. Due to the nature of carbide, that is brittle, the part which has low content of carbide will be ductile. It was characterized by the rough surface which showed the intergranular crack growth as seen in Figure 5(b). On the other hand, due to the high content of carbide former elements, carbides are presence in fine surface and brittle fracture are occurred. It is found the crack along carbides points as seen in Figure 5(c). According to Giang et al. model [20], the carbide particles break first before cleavage occurs in the matrix on the crack plane. In this case, no plastic deformations are observed.

Figure 6(a) to Figure 6(e) show the initial crack zone and crack growth direction in which they are displayed from the macro view to the detailed view. Based on those pictures, crack initiated at the heel side. The heel is one side of the spiral groove (flute) that does not function as a cut side. Due to the inhomogeneous distribution of alloying elements, there is a part which consists alloying elements excessively and there is another part which is lack of them. It is well known that material of end mill is steel alloy in which the most alloying elements are strong carbide former elements such as Mo, V, W, and Cr. The inhomogeneous distribution of them leads to form the non-
stoichiometry carbide points. It is the carbide with excessive carbon content. It is found at the heel part as seen in Figure 6(d). Moreover, Co content in this surface can lead to the dislodging and breakaway of the carbides [6, 21]. It will be diffused with tungsten and carbon and lead to the separation of tungsten and carbon elements, so they will greatly destroy the alloys [22]. The pulling out and removing of carbides were deleterious to the hardiness. The hardiness will be low and not meet the hardiness standard of HSS-Co materials (around 65 HRC). Figure 7 shows the hardiness distribution of fracture surface and surface in distance of 25 mm from fracture surface. The hardiness profiles along the both surfaces are similar where the outer layer is harder than the inner layer. It is due to the surface treatment and solidification process during manufacturing of end mill. Although the hardiness profiles are similar, but the hardiness of the fracture surface and surface in distance of 25 mm from fracture differed significantly. The hardiness of fracture surface is lower than that of surface in distance of 25 mm from fracture. The mean hardiness of surface fracture is 60 HRC, while that of surface in distance of 25 mm from fracture is 63 HRC. Based on the EDS spectra as seen in Figure 8, the surface in distance of 25 mm from fracture contains Cr, Mo, W and V which meet the chemical composition standard of HSS-Co materials. They are the carbides former, so it can be found that fine carbides (bright area) was distributed evenly throughout the surface (Figure 8(e)). They contributed to the hardiness of surfaces. In addition, several points of coarse carbide appeared on the surface (Figure 8(c)). Based on the EDS spectra in Figure 8(d), they are iron carbides.

During the milling process, heat will be generated due to the friction between the end mill and the workpiece so that the working temperature will increase. The milling process must be conducted by providing coolant to avoid the excessive temperature and the damage on both the workpiece and end mill materials. Dry milling process without coolant will increase the temperature up to 770°C [23–26]. It is high enough, but it is not able to alter the micro structure of the end mill material due to its high recrystallization temperature. The temperature also has not been able to cause the elements redistribution in the end mill material during milling process even though the process is repeated many times. Figure 8 is the evidence of this phenomenon. It shows the elements distribution in the used end mill material that has been repeatedly used. Figure 8 was taken at the same position as the fractured surface of the studied end mill. The 4 EDS points in Figure 8 show that the alloying elements were distributed evenly in the used HSS-Co end mill materials. According to Pan et al. (2011), annealing at 780°C for long time, up to 10 hours, does not cause carbide decomposition [27]. Carbide in the end mill will be decomposed if it is annealed at temperature of 1150°C [27, 28]. Briki and Slima (2008) stated that M23C6 carbides are dissolved at 1050°C, whereas M6C and MC carbides are dissolved at 1220°C [29]. So, it can be concluded that high temperature due to friction during the milling process has small possibility to cause failure at the end mill. In addition, if the frictional temperature can redistribute the alloying elements of the end mill material, there will be many end mills failure during the milling process.
The uneven distribution of elements in the end mill material was strongly suspected due to the defective end mill manufacturing process. The manufacturing series of HSS end mill are melting with electro slag remelting (ESR), hot working, hot stripping, annealing, machining and hardening [29]. The machinable round blank of HSS is produced by the first four steps. It can be drilled, turned, broached, milled and tapped to form end mill flutes. End mill is then subjected the hardening process. It is preheated to 871°C, soaked, heated to 1220°C, quenched to 538°C in salt media and finally cooled in air. Based on the Continuous Cooling Transformation (CCT) Diagram, the austenite-to-martensite transformation is controlled by cooling rate. In hardening process, the cooling rate is very high and the transformation of austenite is incomplete and proceeds to form martensite [29]. This process is only related to the phase transformation and the carbides precipitation not to macro elements redistribution. The change of elements distribution occurs only on micro scale that is between carbide grains and its martensite matrix [29]. So it is impossible to blame the hardening process for unevenly distributing of alloying elements.

Part of end mill manufacturing process which strongly lead alloying elements unevenly distribute is electroslag remelting (ESR) process. In the ESR process, the alternating current travelling through the highly resistive molten slag will generate heat and melt the tip of electrode. Melted electrode forms the metal droplets at the electrode tip. They form a molten metal pool in the water-cooled mold after pass through the layer of liquid slag due to the higher density. The molten metal pool is a crescent-shaped in which the center of the ingot is deeper than outward along the radius [30]. Molten metal will solidify and form ingot with the heat transferring to the mold.

Based on the previous studies, the most common and serious defects in solidification of ESR ingots is macrosegregation. It includes the uneven distribution of the solute in the liquid and solid phases [31], interdendritic elemental enrichment [32] and the element redistribution in ingots [33, 34]. Macrosegregation in the ESR process is dominantly affected by the molten metal flow which is triggered by the Lorentz force, the solutal buoyancy, and the thermal buoyancy. The Lorentz force is generated by the interaction between the self-induced magnetic field and the current [31]. The solutal and the thermal buoyancy are created by the large temperature difference between the bottom and top parts. The hotter metal will float up while the colder metal which has higher density will sink down. The temperature difference between the vicinity of the water-cooled mold and the center of pool will form circular metal flow [30]. Macrosegregation is also affected by gravity segregation due to the difference of the alloying elements density. It has the solute-poor and the solute-rich elements formed and segregated [33].

Macrosegregation mitigation methods have been indeed applied in ESR process. The most common method is dissymmetrical cooling system on different surfaces in which the area for the precipitation of segregation solutes was enlarged. The method is proposed to optimize the uniformity of solidified shell and cooling intensity. It will guarantee a regular solidification end. In this case study, end mill HSS-Co was fractured, in which uneven distribution of elements in the end mill material was strongly suspected as the main reason. Macrosegregation in ESR process had the elements distributed unevenly in the machinable round blank of HSS. The dissymmetrical cooling system or apparatus probably was not running or controlled well so macrosegregation was not mitigated during ESR process. It is suspected that the defect was not only experienced by one product of HSS round blank but also the products in the same batch. Due to the defect is macro scale and dwell time is short, austenitization during hardening process was not able to redistribute the alloying elements for making homogenous structure.

During milling process, the end mill is subjected the torsional load due to cutting force and lead to shear stress in the surface layer. The finite element method (FEM) was performed to determine the stress distribution and the location of the critical stress concentration. FEM was conducted by using SolidWorks software. The limit condition of torsional force can be calculated mathematically by equation (1) [35].

\[
T = \frac{60,000 \times P}{2\pi \times N}
\]

where \(T\) is torsional force in Nm, \(P\) is engine power in kilowatts and \(N\) is spindle rotation in rpm. Furthermore, the geometrical condition of tool during side milling of the work piece is indicated by equation (2) and (3) [21].

\[
a_a = 1.5 \times D
\]

\[
a_r = 0.25 \times D
\]

where \(D\) is diameter of the cutting tool in millimeters, \(a_a\) is axial feed depth in millimeters, and \(a_r\) is radial feed depth in millimeters. The geometrical condition of side milling is shown in Figure 10(a). When cutting tools are used, cutting force will be generated and it is illustrated by free body diagram as seen in Figure 10(b). Due to the end mill diameter of 16 mm, based on the equation (2) and (3), the axial feed depth maximum is 24 mm while the radial feed depth
maximum is 4 mm. To simplify the simulation, the con-
stant radial feed depth of 4 mm was set. It was based on
the condition during the end mill was broken. The axial
feed depth was set in the range from 0 mm to maximum of
24 mm. The FEM simulation result displayed the location
and magnitude of maximum stress as a function of axial
feed depth $a_d$ as seen in Figure 11.

Figure 9: EDS analysis of used end mill at the surface adapted to
the surface of fractured end mill (a) points EDS, (b) EDS spectra of
point 1, (c) EDS spectra of point 3, (d) EDS spectra of point 2, (e) EDS
spectra of point 4

Figure 10: (a) Geometrical condition (b) Free body diagram.

Figure 11: Location and magnitude of maximum stress

Figure 12: (a) Meshing, (b) Stress distribution when $a_d$ was 16 mm

Figure 13: (a) Cross section location, (b) Cross section stress distri-
bution
The location of maximum stress was measured based on the end cutting edge surface. When the axial feed depth was in the range from 0 to 14 mm, the location of maximum stress was on the end cutting edge surface while the magnitude of stress decreased exponentially as increasing of the axial feed depth. The location of the maximum stress moved to surface in distance of 48 mm from the end cutting edge surface when the axial feed depth was 16 mm. The location almost reached the boundary area between flute and shank. It was the fracture location. It tended to fix when the axial feed depth was increased up to 24 mm. The magnitude of maximum stress was relatively constant when the axial feed depth was in the range from 16 to 24 mm.

Due to the movement of the maximum stress location, it was interesting to display the stress distribution when the axial feed depth was 16 mm. The meshing of this condition is shown in Figure 12(a) while the stress distribution is shown in Figure 12(b). It showed that the X, Y and Z coordinate of maximum stress location. Moreover, the radial position of maximum stress was also interesting to display. Figure 13(a) shows the cut surface on the maximum stress point, while Figure 13(b) shows the stress distribution on the cross section of surface. It showed that the maximum stress was occurred on the heel side. This FEM simulation results were consistent with the fractography analysis. The location of fracture was almost on the boundary between flute and shank. Crack initiated on the heel side due to the presence of the stress concentration and the non-stoichiometry carbide simultaneously.

4 Conclusions

In this work, the failure of the super hard end mill HSS-Co was analyzed both experimentally and computationally. The experimental investigations showed that the super hard end mill HSS-Co was failed adjacent to boundary area between shank and flute. There were two parts of surface fracture, fine and rough surface. It was triggered by alloying elements that were not evenly distributed in all parts of end mill. Due to the inhomogeneous distribution of alloying elements, there was a part which consisted alloying elements excessively and there was another part which was lack of them. It led to form the non-stoichiometry carbide points. The computational analysis determined the location and the magnitude of maximum stress as a function of the axial feed depth. The result showed that the maximum stress was on the heel side in adjacent to boundary area between shank and flute. It was in accordance with the experimental investigations. Due to maximum stress, the carbide particles break first and crack was initiated. Crack will grow, and cleavage occurs in the matrix on the crack plane due to the torsional load of cutting tool. The inhomogeneous distribution of alloying elements was believed to occur in the round blank manufacturing process, so possible recommendation for avoiding future failures is the quality control improvement of round blank material by increasing the number of controlled samples.

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