An Experimental and Simulation Study on Deep Hole Gundrilling of Inconel-718

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Abstract

This novel study revealed a critical design flaw in conventional gundrilling which prevents effective cooling and lubrication of the carbide drill tips during high aspect ratio drilling of Inconel-718. Gun drills from four international test sites were found to degrade rapidly and fail catastrophically during the process through a cyclical thermo-mechanical fatigue mechanism following intense accumulation of heat on the drill tip that leads to severe adhesion, thermal softening and diffusion. A 3D computational fluid dynamics (CFD) model with full conjugate heat transfer capabilities was developed to investigate the flow behaviour of high pressure coolant and its effects on heat transfer characteristics during the drilling process. To this end, a new deep hole drilling solution for Inconel-718 is under development based on this analysis.

1 Introduction

Gundrilling practitioners are facing steep challenges to construct extremely fine and deep holes on Inconel-718 of exceptionally high yield strength (YS) for the production of advanced oilfield equipment. To a great extent, this constraint is hindering a lot of oil and gas exploration activities in many remote terrains. For the last two years, we have been conducting a series of deep hole drilling experiments at four job shops located in Singapore, Malaysia, Japan and Germany in order to understand the technical limitations involved. This paper reports a key experimental and CFD simulation analyses of a critical thermal-driven phenomenon where conventional gun drills degrades rapidly and fails catastrophically during the process, despite the application of specially formulated drilling oil at high pressure.

2 Experimental Setup and Findings

Fig. 1. Experimental setup of deep hole Inconel-718 gundrilling.

The experimental study was set off to drill holes of 8mm in diameter and depths between 1.6 and 2.0 meters. Cylindrical Inconel workpiece (YS>1000MPa) was supported with heavy duty V-blocks, aligned and then secured to the machine bed. Drills were mounted on the spindle, guided with precision bushings and externally supported on the drill stems. The complete setup is depicted in Fig. 1.

In 16 cycles of drilling, tool wear was universally found to develop on seven regions of the carbide drill tip (Fig. 2a). Although coolant should in theory be able to reach these regions including the flank faces, but in this study, it is almost impossible due to elastic recovery of the newly generated surface. This phenomenon is particularly apparent for high YS Inconel-718 that prevents the drill from cleanly shearing the chips. The magnitude of elastic recovery is directly proportional to material yield strength. Thus, if the rake face is shielded by a growing chip and not receiving sufficient coolant, the flank face will naturally be subjected to severe frictional heating, followed by adhesion and ultimately resulted in notch damage (Fig. 2b). EDS measurement affirmed high contents of Ni and Cr on all flank faces.

Moreover, the gap between the preceding hole and the bearing pads/side margin leaves very little clearance for the coolant to provide critical cooling and lubrication functions. Due to inaccessibility of the coolant and high mechanical loading, extensive abrasive and adhesive wear are resulted. Similar level of Ni and Cr contents were detected on these regions. But more startlingly, an unusually low percentage of cobalt (Co) compared to that of the flank faces was encountered. This indicates Co-diffusive activities on these regions. When the surface temperature exceeds 1000°C, Co becomes unstable and diffuses out of the tool material matrix while dislodges carbide particles simultaneously (Fig. 2c).

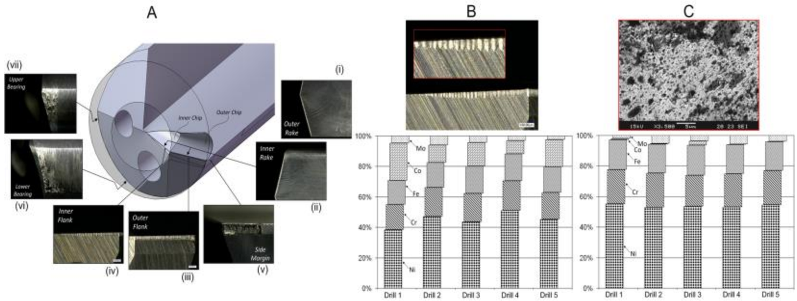

Fig. 2. (a) Steady wear on seven regions; (b) Notch damage on flank; (c) Diffusive wear on drill supports

3 CFD Simulation Setup

A full conjugate heat transfer (CHT) simulation, simultaneously solving for coolant flow field and heat transfer between tool, coolant and the stock material, was set up in ANSYS CFX 14.0. The geometry of the drill and the chip were accurately reproduced; and together, with the thermal and transport properties of the coolant, tool and stock, were input into the package. Areas of heat generation on the drill margin, bearing pad, rake and flank were demarcated as domain interfaces in the CHT model. The SST turbulence model of Menter [1] was invoked for its well known ability to reproduce vortices accurately (Fig. 3).

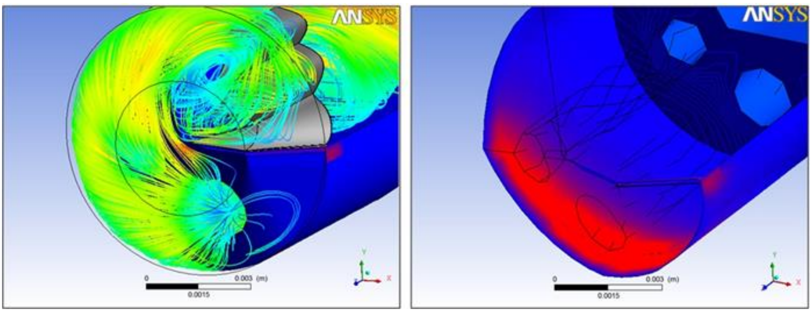

Fig. 3. Flow behaviour and heat transfer characteristics in deep hole Inconel-718 gundrilling.

4 Results and Discussion

Referring to the results in Fig. 3, coolant that is supplied to the drilling point at high pressure will bounce off the hole bottom and diverted rapidly towards the dub-off shoulder. Small amount of coolant is trapped by the growing chip, loses significant energy and forms vortexes around the curvy segmentations of the chip while the rest escapes directly into the v-channel. In essence, the coolant supply will not reach the cutting edges and bearing pads where large amount of heat is generated.

Moreover, chip breaking in gundrilling relies heavily on the coolant supply. In the present case, chips are not broken effectively largely due to the weakness of the conventional design and partially attributed to the high material yield strength. The growing chip will prevent coolant supply to the rake face, leading to a rapid increase in surface temperatures. When the chip is finally broken by its own weight, coolant will be able to cool the rake face momentarily and reduces the surface temperature drastically before the next round of chip formation commences. Our analysis approximates a violent temperature fluctuation of 200°C within 2ms (Fig. 4a). For cemented carbide materials, such magnitude of cyclical thermal loading will cause aggressive expansion and contraction on stress concentration sites on the drills, leading to subsurface crack propagation from the cutting edges and side margins once Griffith's criterion is fulfilled (Fig. 4b). More detrimentally as individual crack front merges with one another, a massive crack propagation network will be formed and ultimately resulted in catastrophic failure of the drill (Fig. 4c).

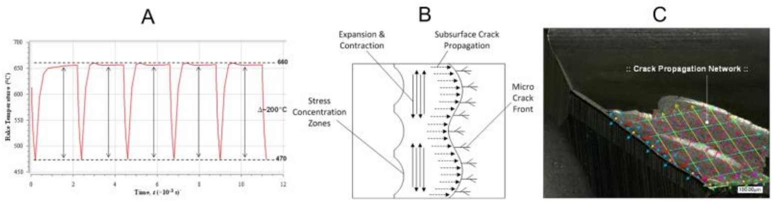

Fig. 4. (a) Thermal loading fluctuation; (b) Crack propagation mechanism; (c) Catastrophic drill failure

Conclusions

The CFD analysis agrees reasonably well with the experimental results which have revealed the critical cooling and lubrication issues of the current practice. A new drilling solution for Inconel-718 is under development to overcome the constraints.

References:

[1] Menter, F. R.,"Zonal two equation k-omega turbulence models for aerodynamic flows", AIAA Paper 93-2906, 1993.