# Tool Life Evaluation in High Speed Milling of Steels for Shipbuilding Industry

Maja Čović and Igor Vujović



September 15, 2020

# TOOL LIFE EVALUATION IN HIGH SPEED MILLING OF STEELS FOR SHIPBUILDING INDUSTRY

**Maja Čović, B.Sc.**
**Igor Vujović, D.Sc.**
University of Split, Faculty of Maritime Studies, Ulica Ruđera Boškovića 37, 21000 Split, Croatia,
mcovic@pfst.hr, ivujovic@pfst.hr

## ABSTRACT

This paper observes tool life tests for different materials used in shipbuilding industry. Materials include stainless steels AISI316L, S235JR, and 42CrMo4V, milled on 5 axis CNC machine, with oil-water emulsion, or with air cooling. Emulsion tested is industrial coolant. The aim is to analyse and compare milling tool life for each material in different conditions, which can optimise machining process. The experiment is conducted in milling centre in Croatia.

**Keywords: Experimental testing CNC machine milling shipbuilding tool life steel optimisation**

## 1. MATERIALS USED IN SHIPBUILDING

Shipyards use milling technologies to produce parts, such as longitudinal and longitudinal and cross side CNC milling machines which mill plates or tank segments, spherical segments, hatchets, profiles, and other small parts used on vessels. Materials used in shipbuilding industry include AISI 316L which is being used in various structures exposed to marine environment, such as tanks and LNG vessels, or material for pipelines on chemical tankers, S235JR, and 42CrMo. Materials were tested on Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture for hardness determination, which provided feed rate while milling. This paper observes test results for tool life while milling those 3 common steels used in shipbuilding industry. Milling is performed in different circumstances, such as milling with oil-water emulsion, and milling without one. Emulsion tested is Kavo coolant 2. The CNC machine used for testing is Yenadent D 43, 5-axis, with specification given in table 1.

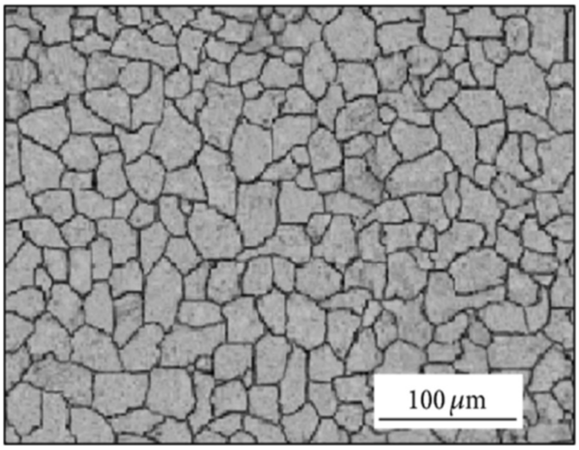
**Table 1. Specification of the machine**

| | |
|---|---|
| MOVEMENTS | 350X230X140MM |
| CONTROL | HIGH SPEED YLS |
| AXIS MOTORS | AC SERVO |
| SPINDLE POWER | 2.5KW |
| SPINDLE SPEED | 60000 RPM |
| NUMBER OF BLOCKS | 1 |
| TOOL CHANGER | 24 POCKET |
| TOOL LENGTH SENSOR | STANDARD |
| WEIGHT | 670KG |
| DIMENSIONS | 100X79X175CM |
| POWER REQ | 220V MONOFAZE 2KW |
| CAM | 5 AXIS |

Stainless steel CrNi has small percentage of (C), going from 0.03% to 0.12%. AISI 316L (X2CrNiMo) has C approximately around 0.03%. Materials used in shipbuilding industry include AISI 316L which is being used in various structures exposed to marine environment, such as tanks and LNG vessels, or material for pipelines.

### 1.1 Stainless steel AISI 316L

AISI 316L is used in various structures exposed to marine environment, such as tanks and LNG vessels, or as material for pipelines on chemical tankers. Hardness of steel used in paper is measured on Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, and is 228 HV10 or 225HB, which implicates improvement and heat treatment of steel. Microstructure of the stainless steel AISI 316L is shown by Figure 1.




*Source: Microstructure, Strength, and Fracture Topography Relations in AISI 316L Stainless Steel, as Seen through a Fractal Approach and the Hall-Petch Law*

**Figure 1: Microstructure of the stainless steel AISI 316L**

Chemical composition of material is shown in Table 2.

**Table 2: Chemical composition of the stainless steel AISI 316L**

| C | Mn | P | S | N | Cr] | Mo |
|---|---|---|---|---|---|---|
| ≤0.0 3 | ≤2.0 | ≤0.04 5 | ≤0.0 3 | 10- 14 | 16- 18 | 2-2.5 |

*Source: Microbial Effects On Heat Treated 316L Weldments In Marine Water. Advanced Materials Research. 794. 606-617.*

Mechanical characteristic of the steel is shown in table 3.

**Table 3: Mechanical characteristics of the stainless steel AISI 316L**

| Hardness, Brinell | Hardness, Rockwell B | Hardness, Vickers | Tensile Strenght, Ultimate | Tensile Strenght, Yieid |
|---|---|---|---|---|
| 149 | 80 | 155 | 515MPa | 205MPa |

*Source: ASM Aerospace Specification Metals Inc., Retrieved from URL.*

Recommendation for 316L stainless steel is for low speeds and constant feed rates, because it tends to work harden if machined too quickly. For lower carbon content, when compared to 316 stainless steel, it is easier to machine.

## 1.2 Stainless steel S235JR

Material used for testing is 125 HV10 or 130HB, tested on 3 different places, and isotopic. Chemical composition % of the stainless steel S234JR is shown in table below.

**Table 4: Chemical composition (%) of the stainless steel S235JR (BS EN 10025, 1993)**

| C | Mn | P | S | N |
|---|---|---|---|---|
| max 0.21 | max 1.5 | max 0.055 | max 0.055 | max 0.011 |

*Source: Evaluation of the properties of S235JR structural carbon steel in Lebanon. Lebanese Science Journal, Vol. 3, No. 2*

With C max 0.21 steel S235JR is a low carbon structural steel. It has good ductile properties as well as excellent weldability. S235JR steel is being used in numerous applications, and one of them is fabrication of water vessels.

## 1.3 Stainless steel 42CRMO4v

**Table 5: Chemical composition (%) of the stainless steel 42CRMO4v**

| C | Si max | Mn | Cr | Mo | S max |
|---|---|---|---|---|---|
| 0.38- 0.45 | 0.40 | 0.60- 0.90 | 0.90- 1.20 | 0.15- 0.30 | 0.035 |

*Source: The Loucefin group. Retrieved from URL.*

Material is tested as harder than S234JR or AISI 316L, with 336 HV10 or Brinell hardness HB 332, which implies the steel is without improvement.

# 2. MILLING PROCEDURE

Tool wear tests are performed in different cutting conditions, with tool wear progression in machining hardened steels are experimentally analyzed.

## 2.1 Tools used for testing procedure

Carbide burs are used for testing, which are observed by microscope and shown by Figure bellow, to analyze tool wear comparison after conducting experiment.

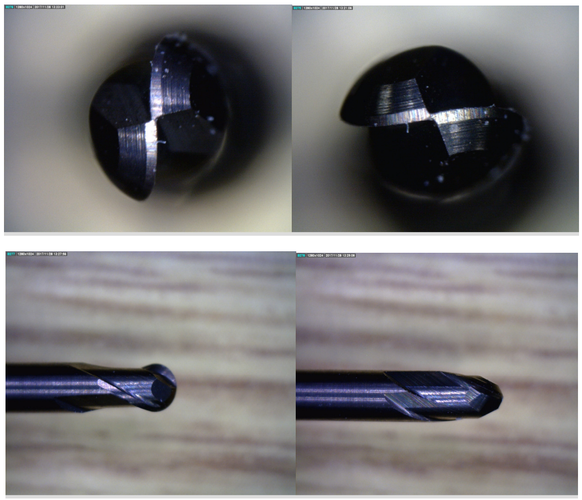


**Figure 2: Images of the surface of a tool used for testing**

*Source: Pictures taken in Laboratory for Metallographic Analysis at Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture*

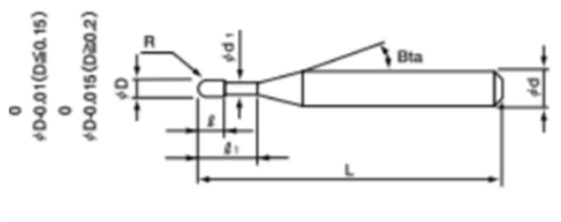


**Figure 3: Geometry and dimensions of tool used for testing**

*Source: Union tool Tungsten Carbide End Mills UNIMAX Series, Volume 17.*

Tools are UNION TOOL's CSELB 2020 120, with tool radius 1mm, or diameter 2mm. Cutting length is 1.6mm and effective length is 12mm. Parameters and geometry of tool are shown below, with experimental conditions of milling. Constants are $f_Z$ = 0.081 mm (feed per tooth); $a_P$ = 0.1 mm (axial depth of cut). The radial depth of cut during the experimental machining was $a_e$ = 0.35 mm.

## 2.2 Mass of tools used for testing procedure

Table shows mass of tools before testing, which will be compared to analyze mass loss after conducting experiment.

**Table 6: Mass of tools**

| **Tool 1 / air AISI 316L** | **Tool 2 / wet AISI 316L** |
|---|---|
| 7.4602g | 7.4648g |
| **Tool 3 air / 42CRMO4v** | **Tool 4 wet/ 42CRMO4v** |
| 7.4592g | 7.4507g |
| **Tool5air / S235JR** | **Tool 6 wet / S235JR** |
| 7.4402g | 7.4547g |

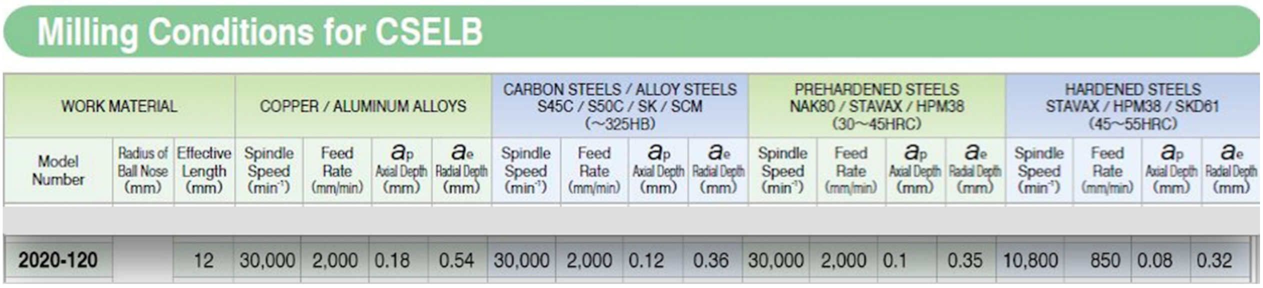
*Source: Table made by author, mass measured on Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture*

Tool 1 is used for air milling of AISI 316L stainless steel, with mass 7.4602g. Tool 2 is used for wet milling of stainless steel AISI 316L, tool 3 is used for air milling of 42CRMO4v with mass 7.4592 [g], and tool 4 is used for wet milling of 42CRMO4v. Tools 5 and 6 are used for air and wet milling of S235JR.

## 2.3 Parameters used for testing procedure

Primary machining variables include speed, feed and depth of cut, and these are shown in Figure 4. Constants are $f_Z$ = 0.081 mm (feed per tooth); $a_P$ = 0.1 mm (axial depth of cut). The radial depth of cut during the experimental machining was $a_e$ = 0.35 mm.

For this study, a test piece was designed and adapted, with two models from which one will be milled with, and another without emulsion. The toolpath is same for both wet and dry testing, for all three materials. Testing is conducted in experiment conditions of milling, with roughing and finishing cycles with same burrs.



Milling Conditions for CSELB

| WORK MATERIAL | | | COPPER / ALUMINUM ALLOYS | | | | CARBON STEELS / ALLOY STEELS S45C / S50C / SK / SCM (~325HB) | | | | PREHARDENED STEELS NAK80 / STAVAX / HPM38 (30~45HRC) | | | | HARDENED STEELS STAVAX / HPM38 / SKD61 (45~55HRC) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Model Number | Radius of Ball Nose (mm) | Effective Length (mm) | Spindle Speed ($min^{-1}$) | Feed Rate (mm/min) | $a_p$ Axial Depth (mm) | $a_e$ Radial Depth (mm) | Spindle Speed ($min^{-1}$) | Feed Rate (mm/min) | $a_p$ Axial Depth (mm) | $a_e$ Radial Depth (mm) | Spindle Speed ($min^{-1}$) | Feed Rate (mm/min) | $a_p$ Axial Depth (mm) | $a_e$ Radial Depth (mm) | Spindle Speed ($min^{-1}$) | Feed Rate (mm/min) | $a_p$ Axial Depth (mm) | $a_e$ Radial Depth (mm) |
| 2020-120 | | 12 | 30,000 | 2,000 | 0.18 | 0.54 | 30,000 | 2,000 | 0.12 | 0.36 | 30,000 | 2,000 | 0.1 | 0.35 | 10,800 | 850 | 0.08 | 0.32 |

**Figure 4: Milling conditions where constants are fZ = 0.081 mm (feed per tooth); aP = 0.1 mm (axial depth of cut). The radial depth of cut during the experimental machining was ae = 0.35 mm.**

*Source: Union tool Tungsten Carbide End Mills UNIMAX Series, Volume 17*

Tools are under maximum stress, to compare better milling without emulsion and with one. Machined area is 68x28mm, and disc used for testing are 95x10mm. Figure shows position of model, and toolpath simulation. Discs are adapted for testing on CAM software used for toolpath development MaykaPicasoft. Figure 5 shows position of model in disc, for milling with and without emulsion. Also, it shows toolpath used for testing, and information as number of points, length of cutting and machining time.

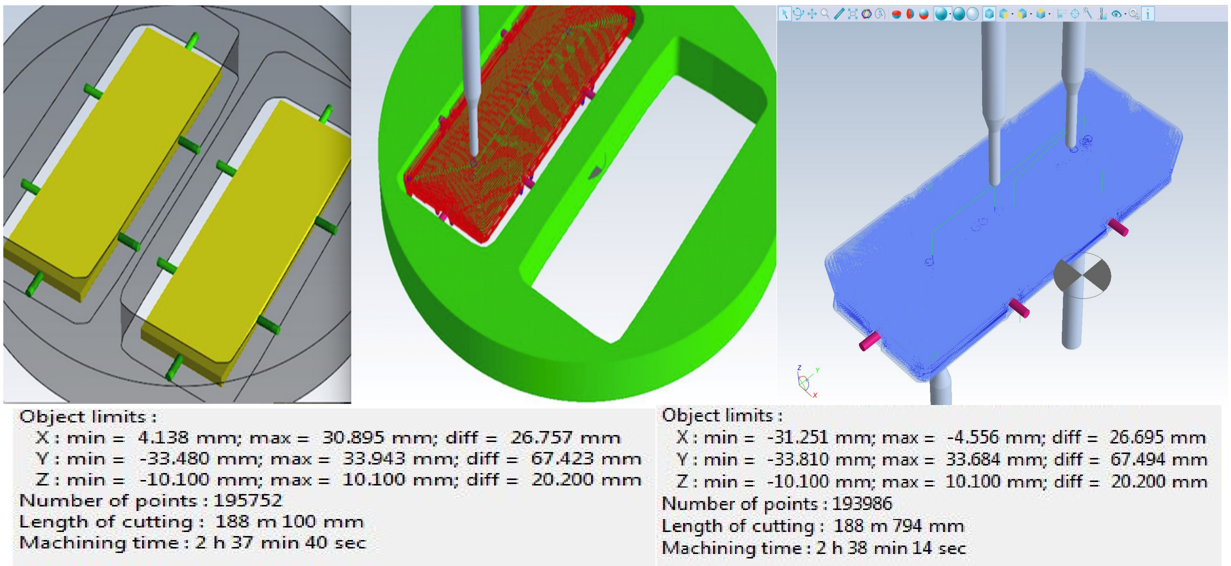



**Figure 5: Position of model, and toolpath simulation**

*Source: Made by author in CAM software MaykaPicasoft*

## 3. RESULTS

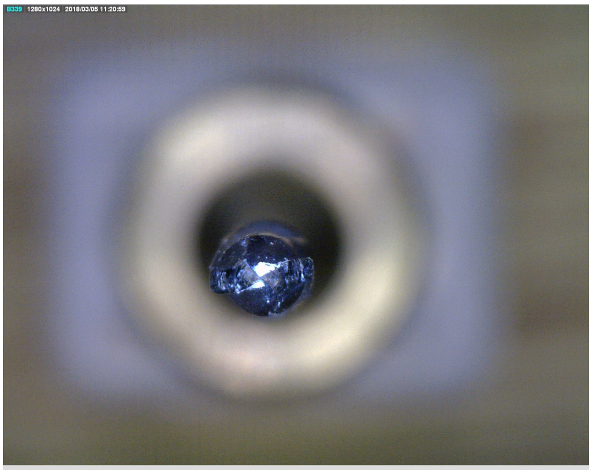
For milling without emulsion length of cutting is 188 [m] 100 [mm], and machining time is 2 [h] 37 [min] 40 [sec], while number of points is 195752. For milling with emulsion length of cutting is 188 [m] 794 [mm], machining time is 2 [h] 38 [min] 14 [sec], and number of points is 193986.

There is a difference in toolpath between milling without emulsion and milling with emulsion of 694 [mm].

### 3.1.1. AISI 316L Milling

Milling without emulsion is conducted with burr number 1 air, mass 7.4602 [g]. Controller position of z-axes is +63.723 [mm] at start. Machine work is stopped after 15 minutes because burr started to overheat, despite the air pressure of 6 bars. Controller in z position is +63.722 [mm] for ending.

For tool number one which was used for milling AISI 316L without emulsion, there was a small amount of mass loss, which was 0.0004 g. Toolwear is minimum, as well as mass loss. Figure 6 - 8 shows tool wear after milling.



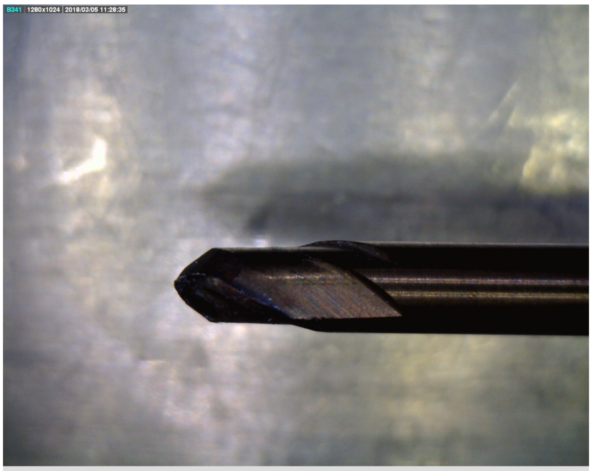


**Figure 6 - 8: Steel part (or fragment) that got magnetized during the cutting processes, and got on magnetic sensors on machine**

*Source: Pictures taken in Laboratory for Metallographic Analysis at Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture*

For milling with emulsion, burr 2 is used, mass 7.4648 [g]. Controller started in position of z axis +63.697 [mm], and ended in position of z axis 63.647 [mm], after 2 [h] 44 [min] 50.2 [s]. Machined measured tool wear 0.050 [mm].

### 3.1.2. 42CrCm4V Milling

Milling without emulsion is conducted with burr 3 air, mass 7.4592 [g]. Controller position of z-axes is +63.733 [mm] for start. Machine work is 2 [h] 45 [min] 14.06 [s]. Controller position of z axis is 63.721 [mm] for ending. Machined measured tool wear 0.012 [mm]. Burr 4 (7.4507 [g]) is used for wet milling, with controller z position +63.577 [mm]. After machine work which lasted 2 [h] 44 [min] 49.74 [s], position of z axis is measured at +63.622 [mm]. Machined measured tool wear 0.045 [mm].

### 3.1.3. S235JR Milling

Milling without emulsion is conducted with burr 5, mass 7.4402 [g], with controller z position +63.499 [mm] at start. Machine milled for 2 [h] 45 [min] 13.46 [s], after which controller had position z= + 63.630 [mm]. Machine measured tool wear at 0.149 [mm].

Wet milling is conducted with burr number 6, mass 7.4547 [g]. Controller measured position of z axis at +63.580 [mm] for starting position, and after milling work which lasted 2 [h] 44 [min] 49.68 [s], ending position measured was +63.630 [mm]. Machine measured tool wear to be 0.050 [mm].

Figure bellow shows steel during milling and steel that got magnetized during the cutting processes, and got on magnetic sensors on machine.

**Figure 9 - 10: Steel part (or fragment ) that got magnetized during the cutting processes, and got on magnetic sensors on machine**

Source: Made by author made in milling centre in Croatia

## 4. CONCLUSION

Tool wear is minimum, as mass loss used for testing, because of short time of toolpath used in this experiment. In that interval, however, it is possible to make preliminary testing and observe behavior of different stainless steels relevant to shipbuilding industry. Milling lasted for 158 minutes for given toolpath. Manufacturer suggests tool life up to 400 minutes maximum.

AISI 316L cannot be milled properly without emulsion with given parameters, but with emulsion it had very good results, with tool wear of only 0.050 [mm]. 42CrCm4V had good results for both wet and dry milling, with small amount of magnetic pieces during the dry milling. Material had slightly better surface quality with emulsion, but tool wear was 0.012 [mm] during the dry milling, and increased to 0,045 [mm] during the wet milling. S235JR steel had good response to both wet and dry milling, but surface got magnetic during the milling without emulsion which affected magnetic sensors. During the wet process, better results were shown. For dry milling, tool wear measured was 0.149 [mm], and 0.050 [mm] for wet milling. Surface quality was worse for dry milling. For all materials, milling with emulsion gave better results on surface quality, but for 42CrCm4V tool wear showed better results without emulsion. Tool had problem with overheating or with magnetic pieces of steel during the milling without emulsion, but tool wear was almost the same for all three materials for wet milling which implicates hardness did not had effect on tool wear. During the testing without emulsion, tool life showed better results for harder materials. Further research should include the use of up-to-date models and methods for high speed milling process tool life optimization regarding steel materials analyzed in this paper.

## ACKNOWLEDGMENTS

*We thank Petar Ljumović from Laboratory for Metallographic Analysis at Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture who assisted the research.*

## REFERENCES

[1] Hilders, O., Zambrano, N., & Caballero, R. (2015). Microstructure, Strength, and Fracture Topography Relations in AISI 316L Stainless Steel, as Seen through a Fractal Approach and the Hall-Petch Law. International Journal of Metals, 1-10. doi: 10.1155/2015/624653.

[2] Suvarna, K., Rajendra, U. K., & Surendranathan, A.O. (2013). Microbial Effects On Heat Treated 316L Weldments In Marine Water. Advanced Materials Research, 794, 606-617. doi: 10.4028/www.scientific.net/AMR.794.606.

[3] Uniontool Europe S.A. parameter calculator UT-APC

[4] Union tool Tungsten Carbide End Mills UNIMAX Series, Volume 17, 338-351.

[5] Source: ASM Aerospace Specification. Retrieved from http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MQ316Q

[6] Sidawi J.A. & Khatib H. (2002). Evaluation of the properties of S235JR structural carbon steel in Lebanon, Lebanese Science Journal, Vol. 3, No. 2.

[7] The Lucefin group. Retrived from http://www.lucefin.com/wp-content/files_mf/42crmo4astmen.pdf

[8] Yenadent Manual for CNC Machines, D43. Retrived from http://www.yenadent.com/Products/Machines/#D43