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ANALYSIS OF THE EFFECT OF TEMPERATURE ON THE PERFORMANCE OF WASTE COOKING OILS USED AS LUBRICANTS ON THREADED JOINTS

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ABSTRACT

To date, considerable research has been devoted to replacing mineral oils with renewable alternatives to reduce the environmental impact of industry. However, the main limitation of vegetable-based lubricants lies in their degradability and poor resistance to high temperatures. A particularly intriguing opportunity is the reuse of Waste Cooking Oils (WCO), whose disposal poses significant environmental challenges. This study investigates, for the first time, the use of WCO as a lubricant during the fastening of threaded joints. Specifically, the nut factor obtained by lubricating a zinc-plated steel screw M10 class 8.8 coupled with a zinc coated nut and tightened on an aluminum substrate is experimentally analyzed. Additionally, to examine the effect of temperature, the joints are subjected to thermal cycles at high temperatures. The difference between the maximum torque measured during tightening and that measured during untightening serves as a descriptor of the lubricant's efficiency loss due to thermal degradation. In order to have a comparison with a mineral oil the tests have been repeated also with the ISO VG 46. The experimental data have been analyzed by means of the ANOVA tools to assess the effectiveness of the input parameters (oil type and aging conditions) on the response in terms of both nut factor at tightening and breakaway torque of the fastener after tightening completion and thermal cycles at high temperatures. Guidelines useful to the design engineer are reported in the conclusions.

KEYWORDS
Bolted; Manufacturing, oil; Testing; Statistical; WCO.

INTRODUCTION

Threaded joints are one of the most widespread joining systems in the world. In order to obtain the desired preload force, different tightening approaches can be used, but the tightening in torque control is certainly one of the cheapest and most used. This procedure consists in using a torque wrench, with tightening torque being applied to the screw head or to the bolt nut and being subsequently increased up to the desired value. The recommended values depend on the required preload force and on the value for the frictional coefficient at the underhead and in the threads [1-4]. Uncertainties on friction coefficients may generate an overestimation or underestimation of the actual clamp force, with consequent screw yield or lack of safety of the joint [5]. For this reason, the frictional properties of threaded connections and the main factors that are likely to affect the tribological response have been the subject of several studies. Some studies have analyzed the effects of different coatings on the friction coefficients [6-7], whereas the effects of tightening speed have been the topic of other papers [8-9]. The evolution of friction in repeated fastening has been studied in [10-12], where the role of wear at the underhead is also emphasized. The effects of oil lubrication and of surface finishing at the underhead have been experimentally studied in [13-15]; moreover the effects of bolt size, thread type and bolt class have been investigated in [16]. Recently there has been a growing interest in replacing mineral oils with vegetable oils, some of which have been tested in bolted joints subjected to repeated tightening, showing good results in terms of friction coefficient [17]. However, the main limitation of vegetable-based lubricants lies in their susceptibility to degradation and poor resistance to high temperatures. A particularly intriguing opportunity is the reuse of Waste Cooking Oils (WCO), the disposal of which presents significant environmental challenges. This experimental study aims at investigating the effect of WCO on the nut factor in bolted joints employing hexagonal-head M10 class 8.8 screws, and the behavior of these lubricants following aging in comparison with a standard ISO VG 46 oil in terms of untightening torque. The motivation of this research arises from the need to understand the frictional behavior of WCO oil and the possibility of using it in bolted joints. The results and collected data have been processed by ANOVA tools [18-19], to investigate the significance of each factor, as well as the related interactions.

NOMENCLATURE

A_t	Stress area
d	Nominal diameter of the screw
d_2	Pitch diameter
d_b	Mean diameter at the underhead
F_V	Axial preload
Ku	Nut factor
p	Pitch
Ra	Roughness (arithmetical mean deviation of the assessed profile)
S_u	Ultimate Strength
S_y	Yield Strength
T	Tightening torque
T_b	Friction torque in the underhead
T_{th}	Friction torque in the screw shank
T_u	Untightening torque
α	Untightening ratio
μ_b	Friction coefficient in the underhead
μ_{th}	Friction coefficient in the thread
ANOVA	Analysis of Variance
C	Number of columns
DoF	Degrees of freedom
Error	Error
$F_{calc.}$	Fisher's ratio[-]
MSQ	Mean Squares (general term)
p-v.	p-value
SSBC	Sum of Squares Between Columns
SSBR	Sum of Square Between Rows
SSQ	Sum of Squares (general term)
SSW	Sum of Squares Within Columns
SSI	Interaction sum of squares
TSS	Total Sum of Squares

MATERIALS AND METHODS

The tests were conducted using class 8.8 hexagonal-head ISO 4017 M10 × 1.5 × 60-8.8 ISO steel screws, with a length of 55 mm and ISO 4033 M10 × 1.5 class 8 steel nuts ISO, that were white zinc-plated. Their technical features are summarized in Table 1. Moreover, for the sake of clarity, a sketch of the threads with related dimensions is shown in Fig. 1. The under-head surfaces were constructed using EN AW 7075 T6 aluminum, with a hole diameter of 10.5mm and a chamfer of 0.5mm x 45°.

Table1.*Main features of the tested steel screws.*

Symbol	Feature	Value	Unit
S_u	Ultimate Strength	800	MPa
S_y	Yield Strength	640	MPa
d	Nominal diameter	10	mm
d_2	Pitch diameter	9.03	mm
A_t	Stress area	58.0	mm^2
p	Pitch	1.5	mm

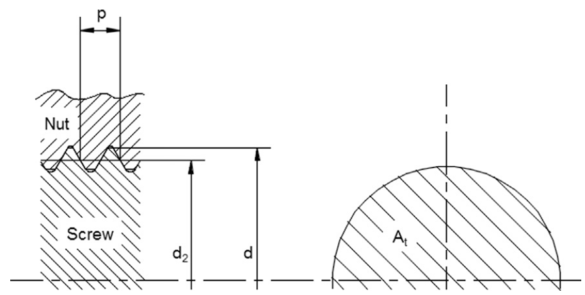

Figure. 1.*A detail of the screw and nut threads with related dimensions.*

To ensure the cleanliness of both the bolts and underhead surfaces, ultrasonic cleaning in paraffin oil by Kemipol®was performed prior to testing, aiming to eliminate any residues from the manufacturing process. A benchtop ultrasonic cleaner (STS-090-T04H300 by Sonixtek®) was utilized for this purpose. The washing lasted 15 minutes at 40°C. During the tests two lubricants were investigated: the VG46 oil Hydro 46 by Arexons®, and the WCO – (Waste Cooking Oils). The oils were characterized following the ASTM D4212 standard, apecifically, a Zhan cup was used [17].

The first tests that were performed aimed at determining the friction in the underhead and in the thread in order to obtain the nut factor. The entire experimentation has been carried out by an equipment capable of simultaneous measurement of both the underhead torque and the preload: Kistler ANALYSE test bench (Kistler, Winterthur, Switzerland), that is capable of measuring both the tightening load and the friction coefficients both in the underhead and in the thread by also directly measuring the torque in the shank and the torque applied by the spindle. The second part of the investigation was focused on the ratio between the tightening and untightening torque. This second test was carried out by means of aluminum sleeves tightened by the bolts. The tightenings were performed in torque control with an electronic laboratory torque wrench (Gedore Torcotronic II 8455-120).

After tightening, in order to examine the effect of time and temperature, the joints are subjected to thermal cycles at room (25°C; 50% humidity) and high temperatures (90°C; 50% humidity) for two weeks and then untightened recording the torque peak. Fig. 3 In order to perform the two parts of the test, underhead plates and sleeves have been manufactured. The first one for the tribological tests with the test bench and the second one for the untightening tests after the aging.

Figure 3: specimens during the aging

The collected data have been processed to work out the friction coefficient in the underhead μ_b by Equation (1), yielded, by inverting the Motosh's formula [3;19], as it is reported in Equations (1-2). The mean contact diameter instead of the actual bearing friction diameter has been utilized because of the low value of the ratio γ between the external and the internal diameters of the contact area between the screw head and the plate [20]. Moreover, the screw head shape generates a pressure distribution at the underhead that does not strongly affect the bearing radius. The nut factor K_u has been calculated by the equation (3). The ratio α between the tightening and untightening torque has been calculated by using equation (4).

$$\mu_b = \frac{T_b}{F_V} \cdot \frac{2}{d_b} \tag{1}$$

$$T = F_V \cdot \left(0.159 \cdot p + 0.577 \cdot \mu_{th} \cdot d_2 + \mu_b \cdot \frac{d_b}{2} \right) \tag{2}$$

$$k_u = \frac{T}{d \cdot F_V} \tag{3}$$

$$\alpha = \frac{T}{T_u} \tag{4}$$

The tightening torque adopted for all the tests as been chosen by some preliminary investigations, where three screws for each oil were tightened until breaking point was reached utilizing the test bench. For these tests, the spindle speed was fixed at 10rpm in order to have a parameter near to a handmade tightening.

RESULTS AND DISCUSSION

As mentioned in the Introduction Section, the present section compares the effect of WCO and ISO VG 46 oil on the nut factor and on the untightening torque for M10 coarse thread metric screws. Before starting with the tightening tests, the two oils viscosity were investigated at room temperature, the VG46 oil shows a viscosity of 84 cst and the WCO 49 cst, the results are summarized in fig.4.

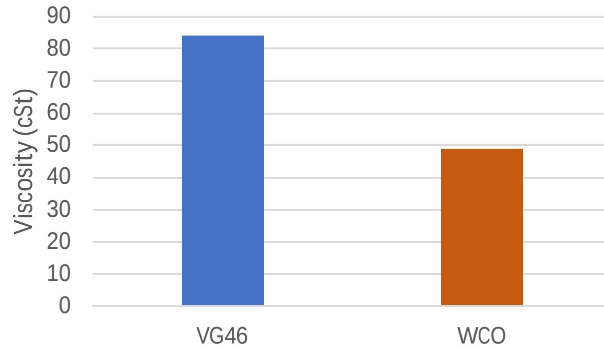

Figure 4: viscosity test

The data collected during the preliminary tightening tests are reported in Table 3 and were utilized to define the tightening torque for subsequent tests.

Table 3. *Results of the preliminary tightening tests*

		Max F	Max T
		kN	Nm
WCO	Specimen 6.1	48,1	84,4
	Specimen 6.2	40,6	79,8
	Specimen 6.3	42,6	77,4
	average	**43,8**	**80,5**
	dev.std	**3,91**	**3,59**
ISO VG 46	Specimen 6.4	47,4	65,0
	Specimen 6.5	44,7	97,1
	Specimen 6.6	45,2	69,1
	average	**45,8**	**77,1**
	dev.std	**1,41**	**17,47**

By the preliminary tests we decided to perform all the tightenings at 54Nm in order to exploit the resistance capacity of the screws and avoid the generation of an axial load exceeding the proof load of the screw. It should be emphasized that the tested screws have largely exceeded the minimum resistances prescribed by the regulations. In the experimental campaign to determine the nut factor all the screws were fully lubricated; in the thread and in the underhead, the results are reported in Table 4.

Table 4. *tightening tests results for WCO and VG 46 oil*

		Max F	Max T	μ_b	μ_{th}	μ_{tot}	ku
		kN	Nm	-	-	-	-
WCO	Specimen 2.1	39,0	54,4	0,09	0,11	0,10	0,139
	Specimen 2.2	41,3	54,2	0,09	0,09	0,09	0,131
	Specimen 2.3	41,4	54,6	0,09	0,09	0,09	0,132
	average	**40,6**	**54,4**	**0,09**	**0,10**	**0,09**	**0,134**
	dev.std	**1,36**	**0,24**	**0,00**	**0,01**	**0,0040**	**0,0045**
ISO VG 46	Specimen 3.1	38,7	54,5	0,09	0,11	0,10	0,141
	Specimen 3.2	38,8	54,4	0,10	0,09	0,10	0,140
	Specimen 3.3	39,0	54,9	0,09	0,11	0,10	0,141
	average	**38,8**	**54,6**	**0,09**	**0,10**	**0,10**	**0,141**
	dev.std	**0,16**	**0,24**	**0,01**	**0,01**	**0,0004**	**0,0002**

The investigation of the data has been started from the effect of the two oils on the nut factor by One-way ANOVA. The result for the nut factor is reported in Table 5. The effect of the oil is related to the term SSBC, indicated in the first row of table 5.

This term is compared to that referenced as “Error” in the second row, which is related to the scattering of the campaign. They are made comparable through division by their degrees of freedom, indicated in the second column. Finally, their ratio ($F_{calc.}$) and the p-v. are computed. The value of the latter indicates that the error probability when asserting that the type of lubricant affects the nut factor is in the order of 6.6%. Therefore, the effect of oil type in this case is not significant.

Table 5. *One-factor ANOVA in the investigation of the effect of oil type*

	SSQ	*DoF*	*MSQ*	$F_{calc.}$	*p-v*
SSBC	0,000065	1	0,000065	6,276845	0,066385
Error	0,000041	4	0,000010		
Total	0,000065	1	0,000065	6,276845	0,066385

The results obtained in the second part of the investigation on the untightening torque and the aging effect are reported in the Table 6.

Table 6. *Results of untightening tests*

ISO VG 46 25°C	T	Tu	α	WCO 25°C	T	Tu	α
specimen COD.	Nm	Nm	-	specimen COD.	Nm	Nm	-
VGA1	53,9	35	0,65	RA1	53,9	35,4	0,66
VGA2	53,9	37,1	0,69	RA3	54	34,4	0,64
VGA3	54	35,1	0,65	RA4	53,7	35,4	0,66
VGA4	54	35,7	0,66	RA5	54,5	38,9	0,71
VGA5	54,3	35,3	0,65	RA6	54,3	28,6	0,53
average	**54,0**	**35,6**	**0,66**	average	**54,1**	**34,5**	**0,64**
dev.std	**0,16**	**0,86**	**0,02**	dev.std	**0,32**	**3,73**	**0,07**
ISO VG 46 90°C	T	Tu	α	WCO 90°C	T	Tu	α
specimen COD.	Nm	Nm	-	specimen COD.	Nm	Nm	-
VGT2	54,5	44,9	0,82	RT2	53,5	46,8	0,87
VGT3	54,4	41,6	0,76	RT3	54,5	45,5	0,83
VGT4	54,2	54,5	1,01	RT4	53,7	53,4	0,99
VGT5	54,5	74,3	1,36	RT5	54,4	48,2	0,89
VGT6	54,1	59	1,09	RT6	53,9	48,9	0,91
average	**54,3**	**54,9**	**1,01**	average	**54,0**	**48,6**	**0,90**
dev.std	**0,18**	**12,94**	**0,24**	dev.std	**0,44**	**3,01**	**0,06**

Five tightening and untightening operations were repeated for each oil-temperature combination. The two types of oils exhibited very similar values of the ratio α at room temperature, with low standard deviation. At high temperature, the VG 46 oil exhibited a ratio close to one, approximately 10% higher than that of the WCO oil, but with an increased standard deviation. The output of data processing using the two-way ANOVA tool is presented in Table 7, where the acronyms SSBR and SSBC respectively indicate 'Sum of Squares Between Rows' and 'Sum of Squares Between Columns'. These two terms correspond to the impacts of the 'row' and 'column' factors, i.e., oil type and aging temperature, as referenced in Table 5, while the term SSI relates to their interaction. The remaining acronyms retain the same meanings as in Table 5, and the quadratic terms are made comparable by division by their respective degrees of freedom.
The results indicate that temperature is the only highly significant factor, with a probability of error (p-v.) on the order of 10^{-5}, confirming that the effect of oil type is negligible. The interaction effect is also not significant at the 5% significance level.

Table 7. *Two-factor ANOVA in the investigation of the effect of oil type and temperature*

	SSQ	DoF	MSQ	$F_{calc.}$	p-v
SSBR	0,02152	1	0,02152	1,32306	0,26695
SSBC	0,46602	1	0,46602	28,65198	0,00006
SSI	0,00991	1	0,00991	0,60955	0,44636
SSW	0,26024	16	0,01626		
TSS	0,75768	19			

CONCLUSION

The main aim of this paper was to investigate the tribological response of WCO oil in comparison to ISO VG 46 oil. The motivation for this study stems from the fact that WCO oil is an underutilized resource, and its application could potentially reduce the environmental impact of bolted joints. The data collected during the tests indicate that the nut factor for class 8.8 hexagonal-head steel screws, coupled with M10 class 8 steel nuts that were white zinc-plated and paired with aluminum EN AW 7075 machined components, falls within the range of 0.13 to 0.14 for both types of oil. Consequently, WCO oil demonstrates lubricating properties equivalent to those of VG 46 during tightening operations. Furthermore, by analyzing the difference between the maximum torque measured during tightening and that recorded during untightening, it is possible to define the ratio α as a descriptor of the lubricant's efficiency loss due to thermal degradation. Even in this case, although thermal cycles influence the loosening torque by significantly modifying the coefficient α, the differences between the two oils under study are not statistically significant. In conclusion, based on the tests conducted, WCO oil exhibits properties comparable to those of VG 46.

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