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Research article

Methodology Experimental Tests on Modified Pin-on-Disc Testing Machine

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A B S T R A C T

The most significant variable in all metal forming processes is the formability of the material. The degree of difficulty determined by this variable is essential for lubricant selection. It is expected that a lubricant will facilitate the sliding of the workpiece in the tool by reducing friction and, at the same time will provide an effective separation layer between the workpiece and the tool.Therefore, in this article, the results of scientific research on preventing damage to the metal sheet surface by lubrication are described in detail.

1. INTRODUCTION

In sheet metal forming industry, friction and lubrication are influenced by many factors such as material properties, temperature, surface finish, contact pressure, sliding velocity and lubricant characteristics [1]. The current literature on this subject argues that sheet metal forming friction and friction related aspects are major concerns as they have a big influence on productivity and product quality [2]. In sheet metal forming a blank of sheet material is deformed plastically and formed to a final shape, as seen in Figure 1. The process is based on sheet deformation caused by the relative movement between tools and a sheet metal, an interaction that generates friction forces. In sheet metal forming process, to produce top quality products, it is important to understand and to be able to control the frictional conditions as the frictional forces influence the formability of the sheet by affecting the strain distribution in various regions of the tool. By controlling the tribological conditions in the process, it is possible to reduce defects or problems, like crack formation, shrinkage, surface deflections (e.g. wrinkles) and severe tool wear.

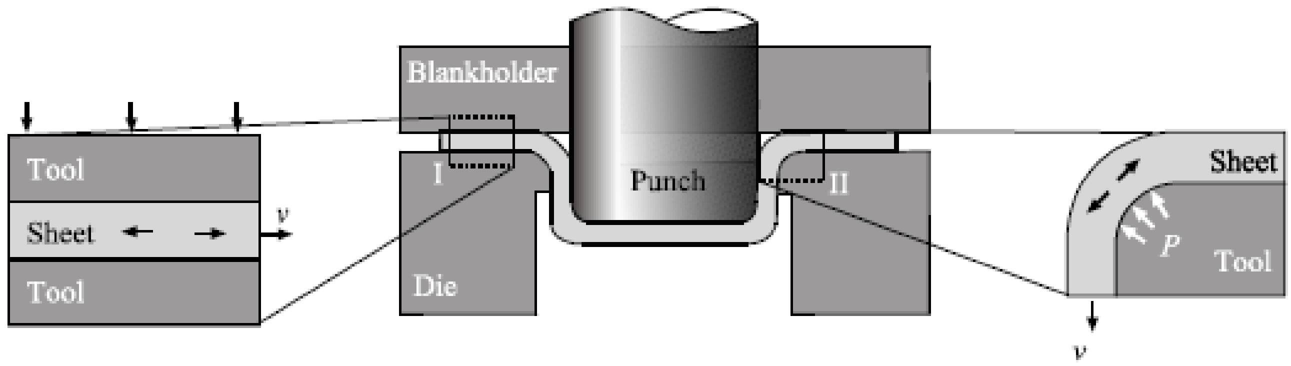


Fig. 1. Schematic illustration of the deep-drawing process, adapted from [3].

Figure 1 schematically presents the main variables related to friction in a drawing process. *P* represents contact pressure and *v* the sliding speed in region I, where sheet is allowed to slide between the blank holder and die; in region II, the highest wear rate of the tool and the sheet is expected, due to a bending and unbending deformation.

Sheet metal forming processes were the main motivation for this study on tribology testing and friction determination. Under these processes the desired shape is achieved through plastic deformation and sliding occurs between sheet metal and tools (punch, blank holder and die).

It is known that press oils and base lubricants decrease the friction between sliding surfaces, by filling the surface cavities and making the surfaces flatter [1]. Therefore, tribology knowledge is essential to understand the importance of friction during the interaction of sheet and tool and dissimilar contacts can be distinguished [3]. The different conditions for each contact may lead to diverse frictional behaviour, which in turn may lead to unacceptable variations in the process or even in rejection of the final product [4], [5]. All sheet metal forming processes have in common that they are mostly performed with the aid of presses which drive the tools to deform the initially flat sheet material into a product. The sliding of a plastically deforming sheet against the tools makes both tribological and mechanical knowledge a fundamental need for optimum processing [6], [7]. Friction between the sheet and the punch/die/blank holder is thus an important factor in sheet metal forming.

Interacting with the lubricant itself, the properties of the tool materials and the surface morphology play significant role with regard to friction and wear as well as workpiece quality.
The success of sheet metal forming depends mainly on three groups of influencing variables [4]:

- the metallurgical properties of the metal and its surface;
- the mechanical forming process and the corresponding machine and tools;
- the type and quantity of lubricant applied, its consistency and its performance features.

The most significant variable in all metal forming processes is the formability of the material. The degree of difficulty determined by this variable is essential for lubricant selection. It is expected that a lubricant will facilitate the sliding of the workpiece in the tool by reducing friction and, at the same time will provide an effective separation layer between the workpiece and the tool. Since the lubricant must contain additives which ensure an effective separation layer during the entire forming process, these additives can change the surface of the metal by chemical reaction. In this way, metal contact between the metal surfaces is avoided. A similar separation effect can be achieved by adding finely distributed solid substances in the lubricant which works as an inert filler or solid matter lubricant.

The drawing tools used for manufacturing high batch productions frequently consist of low wear hard metal materials while less resistant to wear tool materials can be used for small batch productions.The past years have seen steady increases in the use of high-strength steels (HSS), many versions of which are referred to as high-strength low-alloy (HSLA) steels.

Today's most commonly used materials for vehicles continue to be, mainly, different types of steel. They offer a wide variety of material characteristics such as thermal, chemical or mechanical resistance, ease of manufacture and durability. The development process on steel has continuously created new materials for applications within the automotive industry with improved characteristics. These high strength grades are increasingly used in the high-volume production for parts, which are assembled by special manufacturing techniques [8].

Steel is the most widely used material in the world, due to its versatility and competitive costs. Steel is therefore one of the basic ingredients in the development of industry and the whole society. Carbon steel sheet is used in the automotive appliance and building industries. New applications of high strength steels in automotive and other sheet metal forming industries have been increased to the forming capability of steels.

In sheet metal manufacturing, high requirements are placed on the surface finish. Not only for aesthetic reasons but also in order to obtain a surface topography, that is optimal in a forming process. Besides a corrosion attack, the surface may also be affected by mechanical degradation.

2. METHODOLOGY

Under current research work, a methodology has been followed, which included the study and definition of tribological tests, its design and the possibility of implementation. These tests were performed as presented in Figure 2 with modification of pin-on-disc machine, to find the effect of metal properties and other variables on the coefficient of friction.

(a) General view of the reciprocating attachment, (b) Close up view of test specimens

Fig. 2. Modified pin-on-disc machine (Plint TE 67/R).

Large amounts of test equipment for the evaluation of friction properties, often referred to as tribometers, have been designed over the years for a variety of purposes [9]. In this section, only a small number of model tests are presented and these tests merit attention either because of being frequently used, or for representing interesting recent developments in the field of tribotesting.

Reciprocating tests and tested materials

The materials used inexperimental tests included steel alloys those known as high-strength low-alloy cold rolled "HSLA 380" and "HSLA 420" steels which provide increased strength-to-weight ratios over conventional low-carbon steels. For these materials tribology tests were performed with different lubricants.

Lubricants were applied with different combinations. First the sample is cleaned with ether alcohol and after the lubricant is applied with a brush. Lubricants defined as Base lubricants Prelube A and Prelube B were combined with other five different lubricants and as a result there were 12 different combined lubricants.

The sheet was cut to give rectangular samples of 50x20 mm^2. The major length of samples was aligned with rolling direction so that friction tests could be performed along such direction. To minimize irregularities during testing, the samples were carefully deburred and visually inspected to remove test pieces with errors like scratches or imprints of any kind. The initial roughness of the samples measured in the sliding direction was R_a = 1.45 ± 0.20 μm. The rectangular sheet metal samples, were bonded to brass supports as shown in Figure 3.

Fig. 3. Test samples of the steel sheet are stacked on the plate.

A pin-on-disc machine with reciprocating attachment has been used for the tests, using a sphere ball (tool material mounted on pin). The material of the ball used for the friction test is "AISI D2 Steel". D2 steel is an air hardening, high-carbon, high-chromium tool steel, which chemical composition is presented in Table 1.

Table 1. Typical chemical composition of AISI D2 Steel [10].

C	SI	Cr	Mo	V
1.50%	0.30%	12.00%	0.80%	0.90%

Sheet materials

Steel alloys known as high-strength low-alloy steels (HSLA) provide increased strength-to-weight ratios over conventional low-carbon steels. Experimental work under this thesis has been performed using the sheet steel materials HSLA 380 and HSLA 420.

This group of steels is strengthened primarily by micro-alloying elements, contributing to fine carbide precipitation and grain-size refinement, resulting in high strength with low alloy content. This enhances weldability and choice of coatings since these steels exhibit neither weld zone softening nor grain coarsening. The HSLA range of products is available in hot and cold rolled grades. The various grades are identified by their yield strength.

Mechanical properties and chemical composition

HSLA steels with improved formability were developed primarily for the automotive industry to replace low-carbon steel parts with thinner cross section for reduced weight without sacrificing strength and dent resistance. HSLA steels are available in all standard wrought forms -sheet, strip, plate, structural shapes, bar-size shapes and special shapes.

The "low-alloy" means that the strengthening mechanism used in these steels is grain refinement and precipitation due to addition of small amounts of alloy elements such as titanium, vanadium and niobium. Vanadium and niobium additions promote grain refinement, which leads to an increase of the material's strength, especially the yield strength.

Titanium has a great affinity with carbon and nitrogen, leading to the formation of carbides, nitrides, carbonitrides that precipitate in the ferrite matrix, thus contributing with some precipitation hardening that adds to the grain refinement effect.

HSLA chemical composition and mechanical properties in the transverse direction are shown in Table 2 and Table 3, respectively [11,12].

Table 2. Ladle analysis chemical composition of steel sheets HSLA 380 and HSLA 420.

Components	HSLA 380	HSLA 420
C max (wt., %)	0.12	0.14
Si max (wt., %)	0.5	0.5
Mn max (wt., %)	1.8	1.8
P max (wt., %)	0.030	0.030
S max (wt., %)	0.025	0.025
Al max (wt., %)	0.015	0.015
Ti max (wt., %)	0.15	0.15
Nb max (wt., %)	0.09	0.09

Table 3. Mechanical properties of steel sheets HSLA 380 and HSLA 420.

Variables	HSLA 380	HSLA 420
Steel number	1.0550	1.0558
0.2 % proof strength Rp0.2 TD (MPa)	380-480	420-520
Tensile strength TD (MPa)	440-580	470-800
Elongation A80 min TD (%)	≥ 19%	≥ 17%
Availability from Inapal Production	Yes – 1,20 + 1,50 mm thickness	Yes – 1,20 + 1,50 mm thickness

TD - Transverse Direction

Table 4. Surface roughness parameters of the tested steel sheet material before tests.

Steel sheet surface roughness parameters							
Surface condition	Sa	Sku	Sp	Sq	Ssk	Sv	Sz
	μm		μm	μm		μm	μm
Steel sheet HSLA 380	1.23	0.003	19.02	1.52	0.000	-11.60	30.62
Steel sheet HSLA 420	1.28	0.003	24.67	1.57	0.000	-9.76	34.42

Cold rolled HSLA 380 and HSLA 420 are ruled by EN 10268 standard, where they are designated as HC380LA and HC420LA, respectively. The number (380 or 420) refers to the minimum yield strength in transverse direction.

In Table 5 it is presented some surface roughness measurement parameters of a sheet sample. These surface roughness parameters were measured using a Bruker's NPFLEX 3D optical microscope.

Used lubricants for experimental tests

The continuous process improvements and the increased knowledge in metal forming working area have also increased the demands on the lubricants characteristics required for sheet metal forming. The selection of lubricants and their use depend upon various properties and are, in principle, to be viewed from three different perspectives [4]:

- state of lubricant and workpiece before forming and practicable application;
- behaviour during forming;
- corrosion protection and removability of the lubricant after forming.

For the lubricated parts, the coefficient of friction depends on contact pressure, sliding velocity and lubricant properties. On the other hand, an adhesive friction state exists in most of the dry friction regions. Therefore, the coefficient of friction of dry surfaces is usually assumed to depend on the mechanical properties of the steel sheet, such as shear strength and plastic flow stress.

Table 5. Prelube lubricants and ten different combinations with press oils .

Lubricant	Short names	Viscosity [mPa.s]	Density [g/cm3]
Prelube Fuchs Anticorit Pl 3802-395	Base lubricant Prelube A	40 °C 45	24.2 °C 0.900
Fuchs + EMB 1150	Prelube A + Press oil 1	40 °C 58	23.9 °C 0.900
Fuchs + UBO 377.19	Prelube A + Press oil 2	-	-
Fuchs + Renoform EMP 1310 P	Prelube A + Press oil 3	40 °C 85	23.8 °C 0.904
Fuchs + Hakuform 70/2	Prelube A + Press oil 4	40 °C 90	24.2 °C 0.965
Fuchs + Hakuform 20/38	Prelube A + Press oil 5	40 °C 52	23.7 °C 0.897
Prelube Quaker Ferrocote S-6130	Base lubricant Prelube B	38 °C 28	23.3 °C 0.892
Quaker + EMB 1150	Prelube B + Press oil 1	38 °C 46	23.7 °C 0.894
Quaker + UBO 377.19	Prelube B + Press oil 2	-	-
Quaker + Renoform EMP 1310 P	Prelube B + Press oil 3	38 °C 69	24.1 °C 0.900
Quaker + Hakuform 70/2	Prelube B + Press oil 4	38 °C 45	23.9 °C 0.928
Quaker + Hakuform 20/38	Prelube B + Press oil 5	38 °C 37	24 °C 0.897

Therefore, the sliding condition in an actual stamping process is estimated to be placed between the unlubricated condition and fully lubricated condition in friction test. Additional tribology tests were performed to define frictional characteristics of steel sheet materials with lubrication conditions using the two base Prelube lubricants, now mixed with other five different press oils. For these materials, tribology tests were performed with different lubricants, as shown in Table 5.

The idea to combine the corrosion protection properties of a corrosion preventive oil with the lubricity of a drawing oil led to the development of Prelubes. Applied at the finishing lines of the steel mills, they serve as the forming lubricant in the press shops. Adding press oils is only justified if difficult stamping problem has to be overcome.

The use of prelubes in steel mills reduces dramatically the number of spot lubricants for additional press shop oiling. But their benefits can only be achieved if the compatibility principle is applied throughout the manufacturing chain. Therefore, modern prelubes systems are modular, even different viscosities can be part of the same concept. This results in a far-reaching multi-functionality for all applications.

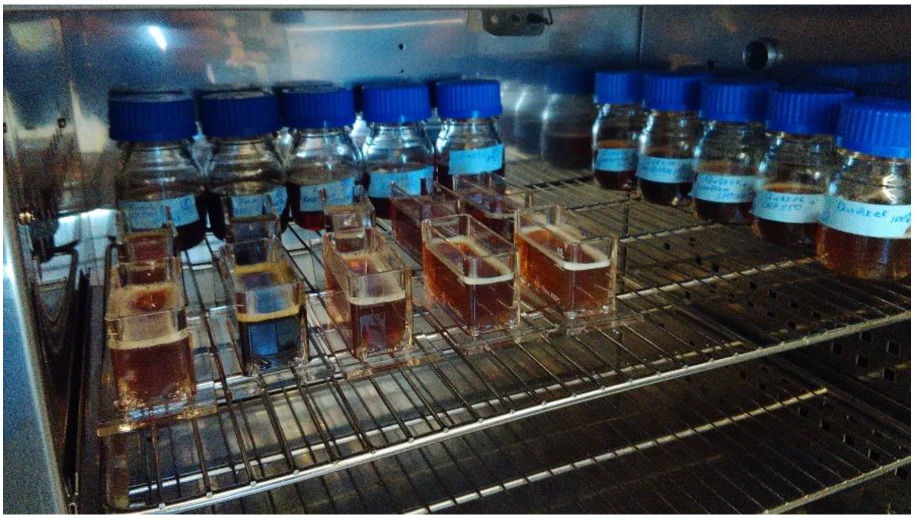


Fig. 4. Preparation of combined lubricants for viscosity measurement.

Figure 4 shows the preparation of different lubricant combinations prior to viscosity measurement. The influence of temperature and pressure on viscosity can be given by means of a VPT (viscosity, pressure, temperature) diagram [13]. The so-called Burns equation for pressure and temperature dependence on the viscosity clearly shows that straight oils have decreasing viscosity η at higher temperatures:

$$\eta = \eta_0 e^{\alpha p - \beta \Delta\theta} \quad (1)$$

In equation 3.1, η_0 is the reference viscosity determined at the reference temperature, $\Delta\theta$ gives the temperature difference, p is the pressure, while α and β give the pressure and temperature dependency coefficients, respectively.

The straightforward temperature dependence on viscosity is only valid if there are no chemically active compounds in the lubricant. Heating accelerates chemical reactions between these additives and the sliding surfaces, causing the lubricant to adhere [13,14]. Eventually it is possible that friction first rises, reaches a maximum and then decreases by this effect. On the other hand, reactivity in the boundary lubrication regime is improved when the temperature increases. However, when the temperature is high, boundary layers can break down, resulting in loss of lubrication functionality, first in decreasing friction and then by increasing friction.

Viscosity index

Of these liquid lubricants, it is especially important to understand the concept of viscosity. Viscosity is expressed as either absolute viscosity or kinematic viscosity. Sometimes the term dynamic viscosity is used in place of absolute viscosity. The absolute viscosity is the ratio of the shear stress causing a flow to the resultant velocity gradient. The viscosity index represents the need to specify how the various classes of oils react to temperature variation. The most used method was proposed by Dan and Davis in 1929 [4]. These authors classified all known oils, at that time, in distinct categories according to the value of its kinematic viscosity (SUS) at 98.8 °C. Annex A presents the measured viscosity variation with temperature of Prelubes Fuchs Anticorit Pl 3802-395 and Quaker Ferrocote S-6130 and their combination with other lubricants.

Density

Density (kg/m^3) is the ratio between the mass and the volume of a body [12,15]. Usually its variation with the temperature is not relevant, however the variation with the pressure might be important as the lubricant film thickness is highly influenced by the contact pressure.

3. EXPERIMENTAL RESULTS

In this work, it is found that the initial lubrication condition is enough to reduce the friction from 0.40 - 0.78 in dry conditions, as seen in Figure 5 to values under 0.12, Figure 6.

Figure 5 shows dry coefficient of friction obtained with varying sliding velocity in reciprocating motion. Each test corresponds only to 40 seconds. Between 40 and 80 seconds the test stopped and therefore during this period the friction line must be ignored. The same is valid for the periods 120-160; 200-240; and 280-320 s.

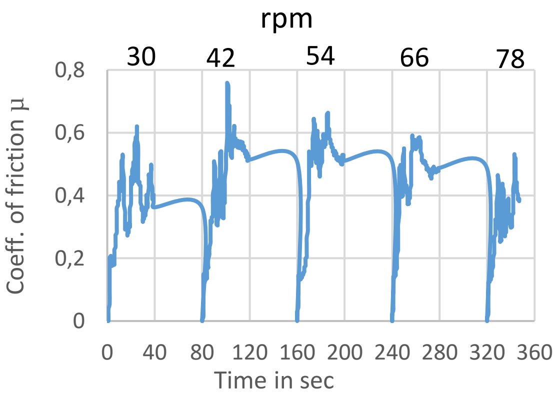
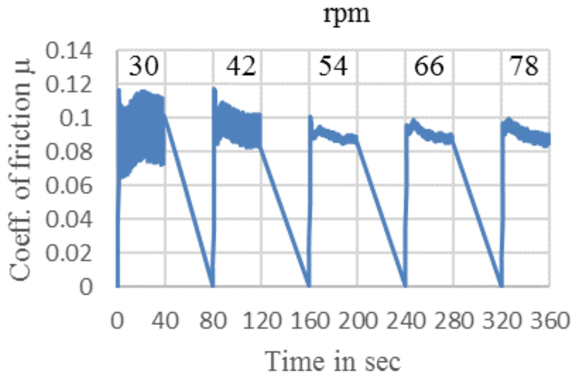


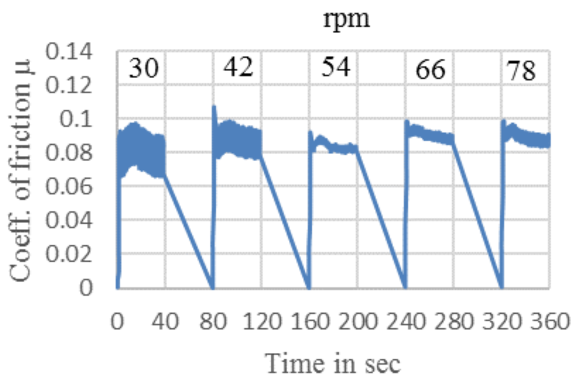
Fig. 5. Dry test - coefficient of friction with varying sliding velocity for "Cold Rolled HSLA 380".

An adhesive friction state exists in most of the dry friction regions. Therefore, the coefficient of friction of dry surfaces is assumed to depend on the mechanical properties of the steel sheet, such as shear strength and plastic flow stress, and it is usually defined as a constant value for simulation or calculation proposes.

Similar tests were carried out using different lubricated condition and the results with Base lubricants Prelube A and Prelube B, are presented in Figure 6 (a) and (b) respectively. The sliding velocity corresponding to the lowest friction is 18 mm/s (54 rpm) for both the Base lubricants Prelube A and Prelube B.



(a) Base lubricant Prelube A



(b) Base lubricant Prelube B

Fig. 6. Lubricated condition - coefficient of friction with varying sliding velocity for "Cold Rolled HSLA 380".

At the sliding velocity corresponding to 54 rpm the smallest value coefficient of friction was obtained and the values are more stable, but at the beginning the coefficient of friction was higher but reducing with time. To summarize, all specified graphs show that the stable values of coefficient of friction are obtained with the sliding velocities 18 mm/s, 22 mm/s and 26 mm/s.

The higher values for coefficient of friction are obtained for sliding velocities 10 mm/s and 14 mm/s. These lower velocities also give higher instability for coefficient of friction.

For the lubricated parts the coefficient of friction depends on contact pressure, sliding velocity and lubricant properties.

Based on these results, the sliding condition in an actual stamping process is estimated to be placed between the unlubricated condition and the lubricated condition in friction test. Additional tribology tests were performed with lubrication conditions using the two base Prelube lubricants, now mixed with other five different press oils and the corresponding results are presented below.

The calculated average values of friction coefficients from previous graphs are presented in Table 6.

Table 6. Average coefficient of friction results of different combined lubricants and varying sliding velocity.

Lubricants	Normal load, [N]	Average linear velocity				
		10 mm/s	14 mm/s	18 mm/s	22 mm/s	26 mm/s
Dry	24.5	0.38	0.50	0.55	0.49	0.41
Base lubricant Prelube A	24.5	0.092	0.095	0.089	0.090	0.091
Prelube A + Press oil 1	24.5	0.079	0.089	0.086	0.084	0.087
Prelube A + Press oil 2	24.5	0.095	0.088	0.096	0.094	0.096
Prelube A + Press oil 3	24.5	0.080	0.081	0.068	0.081	0.082
Prelube A + Press oil 4	24.5	0.095	0.104	0.092	0.098	0.098
Prelube A + Press oil 5	24.5	0.075	0.073	0.080	0.084	0.085
Base lubricant Prelube B	24.5	0.081	0.092	0.083	0.093	0.092
Prelube B + Press oil 1	24.5	0.071	0.083	0.084	0.083	0.081
Prelube B + Press oil 2	24.5	0.096	0.093	0.101	0.102	0.103
Prelube B + Press oil 3	24.5	0.081	0.077	0.079	0.073	0.075
Prelube B + Press oil 4	24.5	0.103	0.10	0.090	0.091	0.090
Prelube B + Press oil 5	24.5	0.078	0.074	0.079	0.081	0.080

4. CONCLUSIONS

Tribological tests were carried out using pin-on-disc machine which aimed to determine the coefficient of friction and behaviour between sheet metal and tools during forming. The research has considered the frictional characterization of reciprocating sliding tests, to find the effect of lubricant and other variables on the coefficient of friction of the cold rolled HSLA 380 and cold rolled HSLA 420 steel sheets with different lubrication conditions.

It is highlighted that: a comprehensive account of the materials, that have been chosen for this work presenting their properties and characteristics that are relevant for the study, lubrication involves not only the selection and formulation of lubricants but also the design of contact geometry, a set of two Prelube oils and its combination with five Press oils have been selected for the study and characterized, two high strength low alloy steels HSLA 380 and HSLA 420 have been elected because they provide increased strength to weight ratios over conventional low carbon steels for only a modest price premium. As HSLA alloys are stronger, they can be used in thinner sections, making them particularly attractive for transportation equipment components where weight reduction is important;

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