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A STUDY ON THE WEAR AND FAILURE OF HOT FORGING DIES OF AUTOMOTIVE CONNECTING RODS

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A significant part of forgings prices is due to costs from reworks of forging dies because of failures on their surfaces. In quest of a higher competitiveness in terms of prices and production times, it is necessary to understand the mechanisms of die failure to increase its working life, avoiding risk situations and a possible total failure of the tools, and also decreasing costs of reworks, maintenance and set-ups, achieving a higher productiveness. Besides known changes to increase forging die life such as forging temperature, stroke speed, lubrication (friction) and superficial metallurgical modification on dies surfaces, it is also possible to increase die life trough geometrical changes of the die profile. In this work it has been studied how the modification of the corner radius, flash land width, depth of cavity, radius of the upper stem, flash thickness and temperatures of forging dies and workpiece influence the wear of the forging of connecting rods in the stem region of the pre-form dies. Through numerical simulation and statistical analysis it was found that the parameters that most influence the process of die wear are the same that affect the die cavity volume which also influence directly the overall width of flash of the forged part. Therefore, the width of a flash is a comparative measure of abrasive wear. It was also analyzed the process of forging in the stem region of connecting rods and it could be verified four distinct stages in the evolution of the abrasive wear, normal stress and forging load. Through this validation it was found that material flow during the process differs from the observed in available bibliographic refererences and it could be also verified a process of upsetting in the rods stem or a radial flow of the rolled workpiece heads toward the rods stem, which tends to increase the diameter of the workpiece stem. Larger diameters increase the process of abrasive wear, therefore being an important factor to be considered in the design of connecting rods dies. From the analysis of the necessary load to forge the stem region of the rod it was verified that the loading pattern is different when the cavity is not completely filled. Finally through the construction of processing maps it can be determined some optimized regions without filling defects, with lower values of wear and thereby increasing die life, keeping the product quality and possibly reducing raw material.

Keywords: *Metal forming; steel; optimization*

1. INTRODUCTION

The high cost of dies required to manufacture forgings parts makes the process selection impractical unless the production volume is large enough to amortize the cost of the tools (Norton, 2000). Moreover, there is a growing demand for parts with an increased accuracy and reliability in mechanical and quality terms, regarding the surface quality and process quality, making the forging processes to continue in a development process to improve cost, quality time and creating a more competitive industry.

According to Summerville (1996), it is estimated that almost 10% of the final forged product value is assigned to the die wear expenses, such as re-work and replacement. Moreover, for Turk et all. (2004) almost 17% of the total production costs are related to forging dies, thus showing a significant portion regarding tools degradation.

For the manufacturing of automotive connecting rods, in general, it is needed about three pre-form dies for each finishing die (ThyssenKrupp, 2008) due to high strain deformation in this first stage that ends up causing premature wear and failure on its surface. Thus, it is extremely important to know the methods and mechanisms that lead to failures in hot forging processes (characterized by the presence of high temperatures, high surface stresses and high tangential loads) to subsequently, improve the tools life and increase industrial productivity.

2. HOT FORGING DIES WEAR

There are many studies for a quantitative method to the prediction of die wear. Babu (2004) examined the pre-requisites for the hot forging tools to resist to abrasive wear and plastic deformation, and then proposed a method to predict the useful life of dies. The author also studied superficial changes in the die surface due to contact with the workpiece and its influence on the process of abrasive wear.

At high temperatures a process that significantly affects the life of the dies are superficial micro-structural changes that occur due the heating of the die that during forging and that may cause surface temper. This layer may ultimately cause failures and cracks on its surface (Summerville, 1996 and Behrens, 2008).

Another possible process present during wear is the surface softening of the dies as result of many and many repeated forgings (Kang *et all.*, 1998). Many studies consider the tools surface hardness as constant or as function of the workpiece temperature following the model proposed by Archard in 1953. However the forging time dies are used is an important factor to predict surface hardness. Works done by Behrens (2005 and 2008) have a modification of the model of Archard and take into account the variation of the die surface hardness due to thermal effects.

However, the useful tool life is affected by several variables and differ from case to case. In general and in a simple way their are equivalent to parameters that affect the process of hot forging, such as lubrication, die temperature, workpiece temperature and stroke. Grobaski (2004) studied these parameters and their influence on wear in hot forging, in which it is possible to notice the temperature as the most influential parameter in the die degradation and forging load.

Cser *et all.* (1993) proposed at his time the existence of many parameters of influence for tool life, such as lubrication, geometry, die surface heat treatment, materials involved, die roughness, temperature and others. According Kannappan (1970) the main methods of degradation of hot working tools are: abrasive wear, thermal fatigue, mechanical fatigue and plastic deformation, in which more than 70% of the cases presents abrasive wear. Figure 1a shows the thermal fatigue, normally found in regions where the contact time between workpiece/die is higher. Figure 1b shows a micrograph of the central region of a hub die in which it is possible to see the die deformation in the direction of the material flow causing poor dimensional tolerances (Summerville, 1996). Figure 1c shows a crack caused for mechanical stresses (ThyssenKrupp, 2008) and in Fig. 1d, the abrasive wear in the corner radius, at the transition from the die cavity to the flash land.

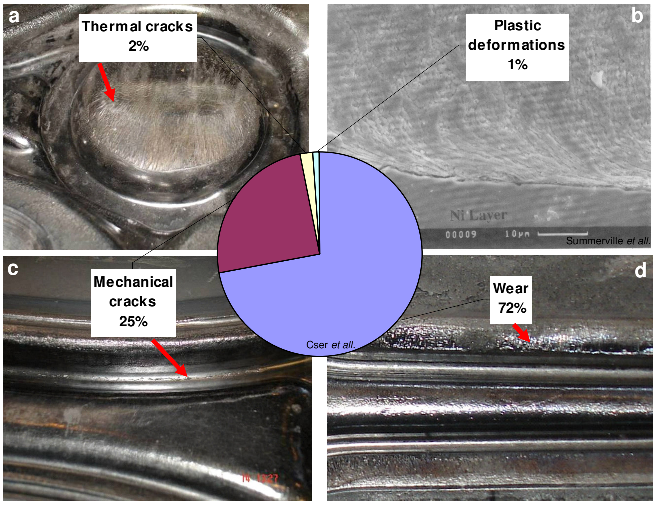

Figure 1.1. Tool failure mechanisms and frequency

Another mechanism of forging tools degradation, however more frequently for cold working process, is the adhesion wear, as result of a micro-welding between the workpiece and die surfaces due to irregularities of the tools and a subsequently wipe off of die material with the workpiece flow, more deeply studied by Doege *et al.* (1990).

2.1. Wear calculation

The numerical simulation software used in this work was FORGE 2007, based on finite element method, which uses a modified method of Archard to calculate the wear on dies surfaces, Eq. 2.1. This is a reliable model when there are adequate input parameters for simulation, but it is not very accurate because in their calculation are not considered other factors such as variation in the surface hardness of the tool over time as previously mentioned.

$$Wear = \int (\sigma_n * \delta V)\delta t\_contact \qquad \text{(Eq. 2.1)}$$

Where:

σ_n = Normal Stress in δt of contact

δV = Tangential velocity

Unit of wear = Unit of stress [MPa] * unit of lenght [mm].

3. CURRENT PROCESS ANALISYS

The production of conrods is normally done in five steps: initial raw workpiece heating in ovens, preparation of raw material by rolling, which in this case may be cross rolling or longitudinal rolling, pre-form forging, final forging to give a final calibration of the forging dimensions and finally, deburring. This work will study the process in the first stage of forging (pre-form). Figure 3.1 shows the dimensions of the rolled workpiece before being forged and the dimensions of the final product in decimeters to give a idea of the con rods dimensions. It is possible to see the stem region of the rod, which will be object of study in this work. This rod is forged in a mechanical press with 1180 º C and its composition is similar to SAE 1070 steel.

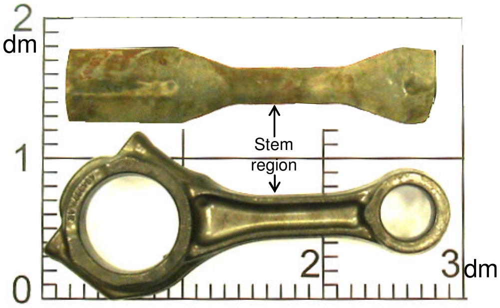

Figure 2.1. Dimensions of rolled workpiece and final conrod.

3.1. Upsetting analysis in stem region of the rolled workpiece

The initial diameter of the rolled workpiece in the stem section is 29 mm, however a fact that comes to mind is the flow process in this region. According to ASM Handbook (1996) for a similar geometry the flow should be totally plane in all areas. However through an analysis by numerical simulation (Forge, 2007) of the rods profile when it touches the upper and lower die cavities, it is possible to observe that the diameter is 29.6 mm for (2.1% of upsetting). Figure 3.2 shows the displacement of material in the "X" direction from the regions that form the rods eyes to the center, thus showing the process rods upsetting process.

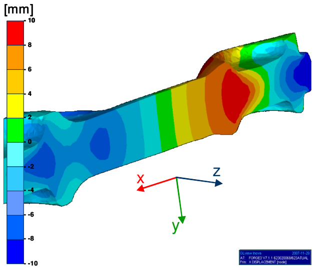

Figure 3.2. Rods stems upsetting process when upper and lower die cavities touch the stem region of the workpiece.

At the presence of the two larger volumes at the workpiece corners, they begin the process of forging before the region of the stem, Fig. 3.3a. Thus, there is initially a radial flow of the eyes in all directions, providing enough pressure to upset the stem, which does not offer any resistance and for being in high temperature decreases the force required for upsetting by increasing the steel conformability. It is expected that the process of repression ceases when the stem touches the cavity and starts the process of forging by offering resistance in the opposite direction, Fig. 3.3b.

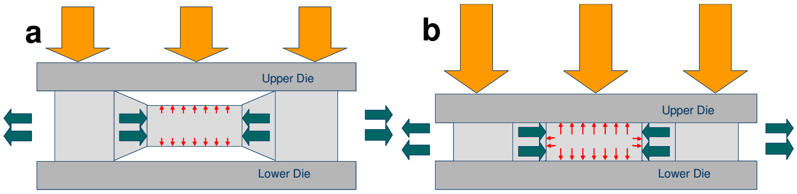

Figure 3.3. Conrod stem upsetting process, (a) forging start, (b) moment when the workpiece stem touches upper and lower die cavities.

However this assumption is not true as shown in the analysis of the cross section of the stem, Fig 3.4, and measuring of the equivalent diameter, Eq. 3.1, using the surface area A_t.

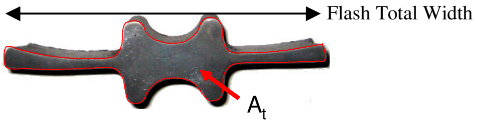

Figure 3.4. Stem cross section for equivalent diameter analysis.

$$D_{eq} = \sqrt{\frac{4 \cdot A_t}{\pi}} \tag{1}$$

From experimental measurements it was obtained that $A_t = 7.2 \pm 0.17$ dm^3 and the equivalent diameter for this section is $D_{eq} = 30.3 \pm 0.35$ mm, showing that the process of upsetting continues even after the region of the stem rod touch the cavities. This fact is due to differences of volume and pressure, thus the pressure exerted by the stem is not enough to block the pressure from the eyes regions, making the upsetting to continue until the end of the forging of the rod.

3.2. Analysis of forging load in the stem region

According to Dieter (1981), it is possible to predict the internal die cavity fill by graphical analysis of the forging load, however unlike the method proposed by the author, the loading curve is not smooth, but when there is a total fulfillment, there is a sudden increase of force, and then it is more evident the moment when the cavity is filled. Figure 3.5 shows the forging of a stem section and the possibility to verify the moment the cavity is completely filled, at the sudden change in curvature of the forging load.

Moreover, it can be noticed that there are four distinct stages in the process, which can be viewed in Fig. 3.5 as a function of the upper die displacement.

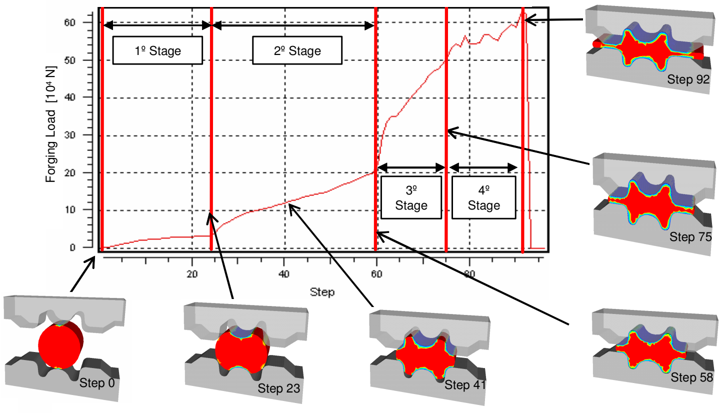

Figure 3.5. Forging load analysis for the stem section.

The first stage is a free forging of the center of the section which extends from the beginning of the process (step = 0) until the moment when the workpiece touches the radius of transition of the flash land region (step = 23). In the case of a free forging, and without restriction to the material flow, the load is low as the normal stress, and as the material flow has not high tangential speed to the dies; the wear is low. The second stage begins when the material is already with the restriction of flow at the radius of transition and it begins to fill the internal cavity of the dies. As there were added points of restriction to the material flow, forging load and normal stress tend to increase slightly compared to the previous stage. The beginning of the third stage (step = 58) occurs when there is complete fulfillment of the cavity and with the formation of dead zones of flow it tends to increase significantly the load and normal stress. Due to the increase of normal stress, the wear begins to increase gradually with decreasing of flash thickness and increasing of tangential velocity. The fourth and last stage (step = 75) is observed when the material flows out of the flash land, finding some normal stress relief and forming a different pattern in the curve of loading.

Such graph pattern can also be explained by the friction at the interfaces of forging. Figure 3.6 shows the energy of friction in this process, and again it can be clearly observed the four stages of the rods stems forging.

Although the lubricant is highly influent on the process of forging (Batelle, 1982), it was chosen not to use a lubricant in all simulations. Its presence would significantly modify the final values and probably that standard curves of forging load and friction power.

Another interesting point to be analyzed is how the evolution of forging load, the normal stress to the die surface and wear take places together. The graph represented by Fig. 3.7 combines these three responses in a single standardized graph.

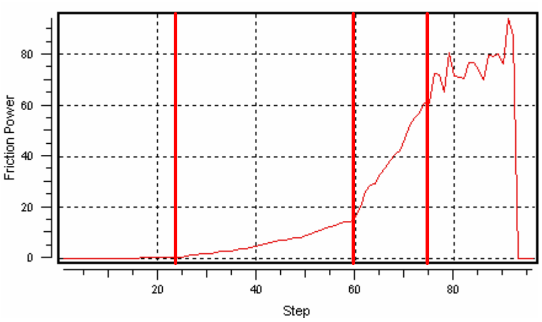

Figure 3.6**.** Friction power analysis.

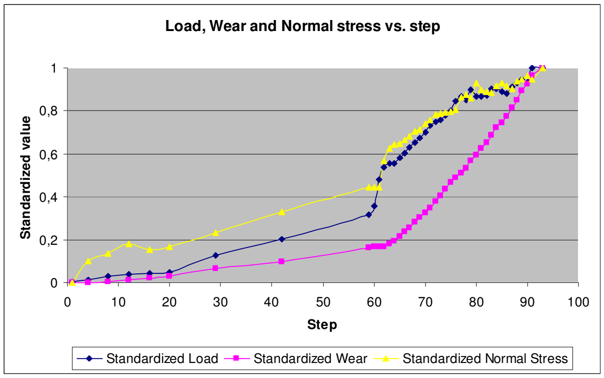

Figure 3.7. Standardized load, normal stress and stress vs. simulation step.

For the normal stress the pattern follows clearly a similar behavior to the forging load with changes visible to the steps of simulation approximately of 20, 60 and 75. However for the wear it is not possible to observe the beginning of the last step (step = 75), so the wear is not influenced by outgoing of the material through the flash land as the other two responses. But it will be shown below that the total length of the flash is directly related to the abrasive wear present in the dies.

4. DESIGN OF EXPERIMETS FOR THE NUMERICAL SIMULATION

In this work the numerical simulations based on the finite elements method (Forge, 2007) were done with the hypothetical profile of the stem region of the dies and with a cylindrical workpiece with 29.6 mm in diameter, i.e. with the same effect of upsetting at the time the upper and lower dies touch the stem in the actual process. As can be noted this is a two-dimensional model, however it was undertaken as a three-dimensional one (thickness of 3 mm) for mitigation of any errors from the software simulation.

4.1. Experimental design – 1st Part

In this work the following variables were considered significant to the process of the pre-form forging, as illustrated in Fig. 4.1. Note the five geometrical variables and two temperatures. Again the lubrication will not be considered despite it is a very important factor for die wear, due to the complexity of control at high temperatures can interfere significantly in the final results.

As the objective of this study was to analyze the influence parameters on die wear, all the variables must vary in the same percentage to determine the parameters that most affect the process. For this, it will be taken a variation of 10% for all variables, because a higher change would result in a higher forging temperature over the acceptable for the process and other dimensions would extrapolate the allowed dimensions for the internal geometry of the cavity. It is of common understanding that some variables can vary more than others, however, all were fixed around the zero and varied in the same proportion in order to highlight the most influent. Table 4.1 shows the variation of parameters and their levels.

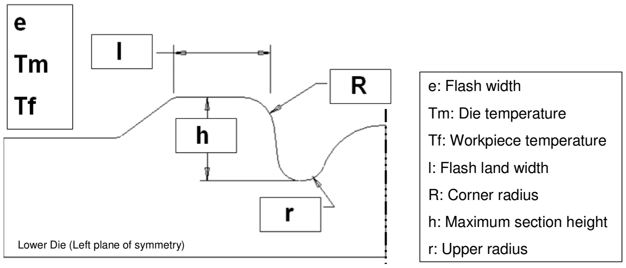

Figure 4.1. Process variables related to the die geometry

For this design it was chosen the design of experiments full factorial 2^k (Box, 1978), i.e. to this part, $2^7 = 128$ simulations. Although there is no need to perform a full factorial, it was choused to do so to exclude any doubt of the influential parameters and generate better results for future analysis.

From the data obtained will be constructed and the Pareto charts and Main Effects Plot for forging load, abrasive wear and total flash width, being possible to examine the influence of the parameters studied for process as a whole. In the graphs of Main Effects were added center points to check the curvature of the test (Box, 1978).

Table 4.1. Factors levels

Factors			(-)	0	(+)
A	**[mm]**	**R**	3,65	4,05	4,46
B	**[mm]**	**r**	2,52	2,80	3,08
C	**[mm]**	**e**	2,88	3,20	3,52
D	**[mm]**	**L**	11,43	12,7	13,97
E	**[mm]**	**h**	9,28	10,31	11,34
F	**[°C]**	**WP Temp.**	1062	1180	1298
G	**[°C]**	**Die Temp.**	180	200	220

4.2. Experimental design – 2nd Part

After the verification of the variables effects on the forging, it was done the optimization of the process by building an optimization process map. For this, it was done another series of simulations with other matched factors, or in other words, a set of groups of two factors with greater variation of their levels around the zero.

For the first experiment the flash land width (L) was analyzed with the flash thickness (e). Then the corner radius (R) with the flash thickness (e), after that, the forging temperature (Tf) versus flash thickness (e) and finally the initial workpiece diameter (d) with the flash thickness (e). From these results, it was possible to verify the most influent parameter compared to the results of the first experimental design, and at what levels dies cavities had failed. From this analysis it was built up optimization process maps for the forging process.

5. RESULTS AND DISCUSSIONS

Given a level of significance (Box, 1978) $\alpha = 0{,}005$, it was built up the first Pareto charts and then the Main Effects Plots for the most significant parameters.

5.1. Forging Load

It can be noted by the Pareto chart of Fig. 5.1a that the most influent parameters for the forging load are respectively: the forging temperature (Tf), the flash land width (L) and the flash thickness (e). In the Main Effects Plot, Fig. 5.1b, an increase in flash thickness results in a lower load, an increase of the flash land width results in an increase of the load and finally, higher temperatures reduce the forging load.

The forging temperature (Tf) is directly related to the workability of the material, and lower forging loads are achieved. The flash thickness (e) is related to the degree of deformation of the material, the greater the degree of deformation, the greater the force necessary to forge (Dieter, 1981). The increased of forging load due to the increase of the flash land width (L) can be explained by the increase of the surface area in this region that will generate higher difficulty in the material flow for the burr due to friction.

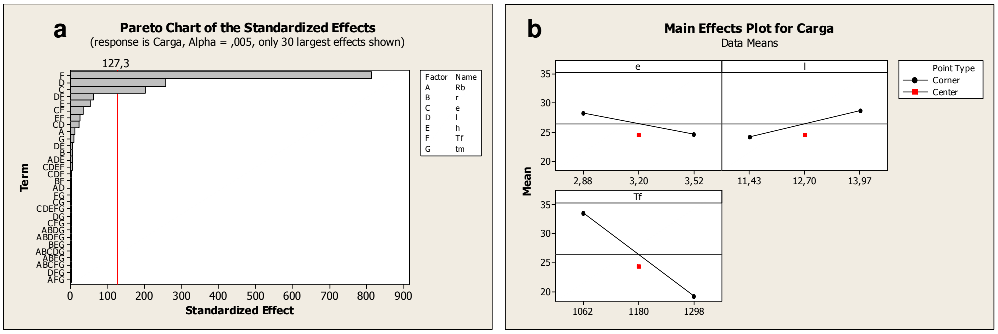

Figure 5.1. Pareto chart (a) and Main Effects (b) for forging load.

5.2. Abrasive wear

For the abrasive wear it can be seen from the Pareto chart, Fig. 5.2a, the most influent parameters are: forging temperature (Tf), the flash thickness (e), the maximum section height (h) and flash land width (l). In the next graph, Fig. 5.2b, it can be noted that an increase in the maximum section height (h) reduces wear, higher temperatures of forging (Tf) reduce wear, greater flash thicknesses (e) lead to a decrease of the total amount of wear and finally, increasing the flash land width (L) also increases the abrasive wear.

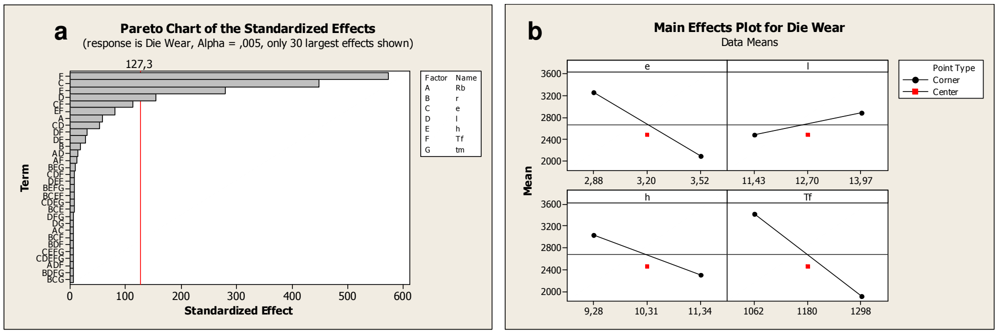

Figure 5.2. Pareto chart (a) and Main Effects (b) for abrasive wear.

Although the forging temperature (Tf) provides a high influence on the process, both for the forging load and for the wear, as seen in Fig. 5.1 and 5.2, this is not an interesting parameter to be changed because of the possibilities of internal melting that may lead to internal failures. Furthermore, an increase of Tf increases the speed of surface oxidation, promoting a greater number of abrasive particles that will assist in the process of abrasive wear and also an excessive increase of the die temperature, which, as seen previously, may lead to its weakening and decrease in its surface hardness.

The forging temperature (Tf), the flash thickness (e) and flash land width (L) influence the process of wear by increasing the forging load as seen above, therefore the normal stress present on the surface will increase, and as the calculation of abrasive wear (Eq. 2.1) is a function of normal stress, its value will increase. Nevertheless one curious fact to note is the maximum section height (h) as an influencing factor to the process. By visual analysis of the simulations it was noted that with an increase in the maximum section height in addition to reducing the wear, reduces the total length of the flash, Fig. 3.4. So the next step is to examine the parameters which affect the total flash width and then examine the importance of the maximum section height.

5.3. Total flash width

Changes in the geometry of the dies affect significantly the total flash width, so by the Pareto chart seen in Fig. 5.3a and main effects, Fig. 5.3b, it can be noticed the influence of the parameters on this response. Note that in the Pareto chart there are parameters taken as influent to the process with the given level of significance, however it was made the Main Effect Plot only for the first three. It can be observed that a decrease in flash thickness (e) greatly increases the total flash width, an increase in the flash land width (l) generates a small increase in the total flash width and an increase in the maximum section height (h) influences significantly to an increase of the total flash width.

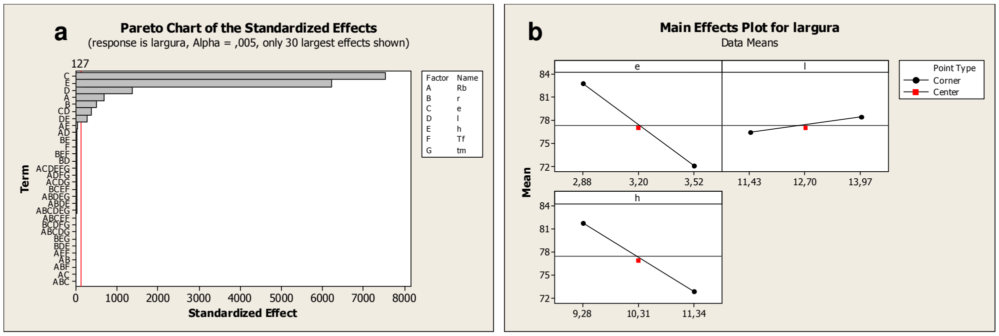

Figure 5.3. Pareto chart (a) and Main Effects (b) for total flash width.

In a first moment it can be made a correlation between the total flash width and the internal cavity volume, the greater the change in the internal volume the greater will be the change in the total flash width. In the Pareto chart for the internal volume of the cavity, Fig. 5.4a, it can be noted that the three most influential are also the maximum section height (h), flash thickness (e) and flash land width (L). Figure 5.5 confirms this correlation of the internal cavity volume with the total flash width.

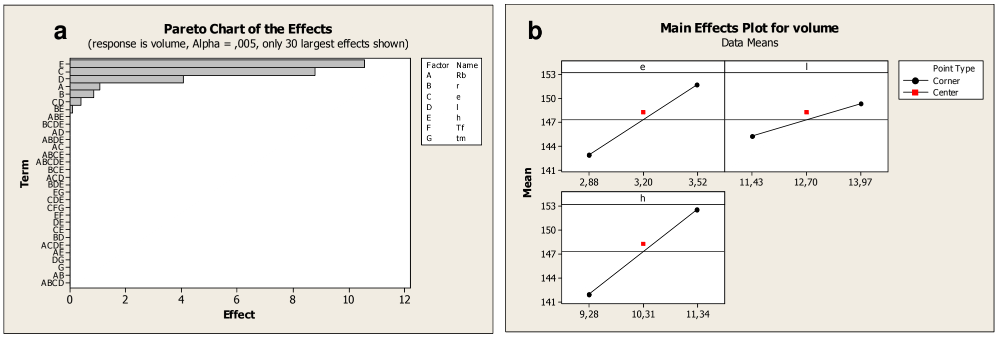

Figure 5.4. Pareto chart (a) and Main Effects (b) for die cavity volume.

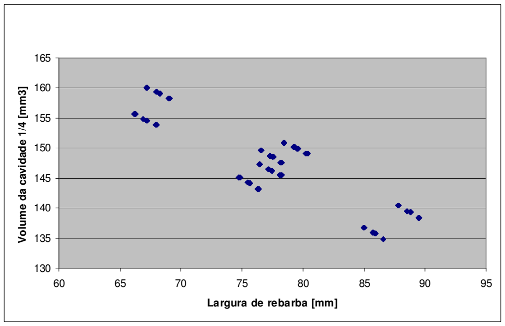

Figure 5.5. Cavity volume versus total flash width

5.4. Analysis of the abrasive wear as a function of the total flash width

Another interesting point to be noted is that the same parameters that affect the abrasive wear are the parameters that affect the total flash width. Thus, a correlation between total flash width and wear was shown by Fig. 5.6.

It is possible to verify that an increase in the total flash width from a decrease in the internal cavity volume causes an increase in abrasive wear.

Another fact that can be explained is why the maximum section height (h) is considered as an influent parameter on the process of wear. Since this variable affects directly and significantly the internal cavity volume and the total flash width, the less material leaving the flash land for the burr formation, the less will be the wear present. This is due to the fact that the larger the amount of volume that exits the flash land at the moment the cavity is filled the greater the tangential velocity on the dies surfaces, and with the addition of a high normal stress high, generates higher values of wear.

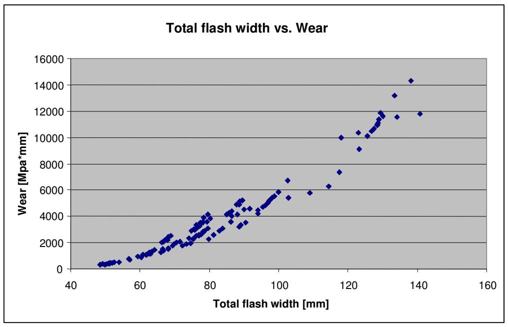

Figure 5.6. Relation between Wear and Total flash width.

5.6. Optimization process maps

The graphs presented in Fig. 5.7 and 5.8 were generated from the second part of the experimental design, Section 4.2. The full blue lines represent the level curves for loading while the dashed lines in red represents wear. Since for small loads of forging the dies cavities were not fulfilled for both variation of flash thickness (e) versus maximum section height (h) and for flash thickness (e) versus initial workpiece diameter (d), this response was taken as limiting to the process (region of die filling failure). With the on-position of both the graphics-level curve, it was created an optimization map of the process. It is possible to check that in both cases the current process is in a region that can be improved, reaching the zone of low load and low wear (light green) and outside the critical region (red zone).

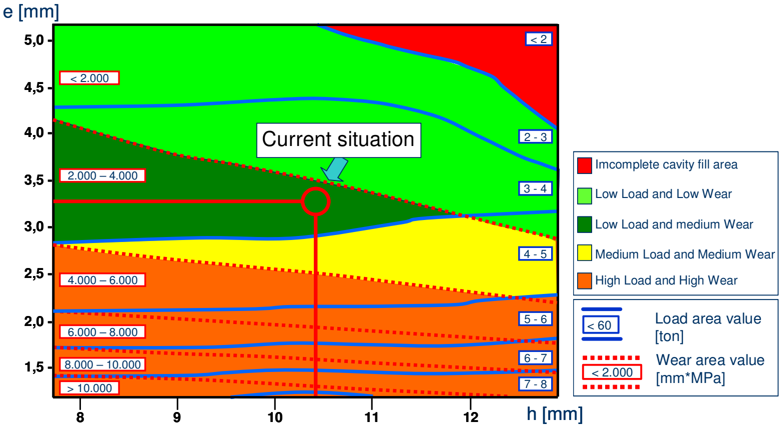

Figure 5.7. Optimization process map, Maximum section height vs. Flash thickness.

In the last graph it can be seen that there is a possibility of working with smaller initial diameters of the workpiece, generating lower normal stresses by creating smaller dead zones of metal flow and lower tangential speeds on the flash land region.

The experimental work of Fereshteh-Saniee (2006) shows that as larger the flash, the greater the forging load and consequently as seen in this work, is the abrasive wear. Thus, one possibility is to reduce the volume of flash through both increasing the volume of the internal cavity of the die and decreasing the initial volume of the workpiece. Leaving the rules that specify the volume to the flash and entering a process of Near Net Shape or even flashless process with an optimized geometry of the initial rolled workpiece.

A simple decrease in the diameter of the rod at the stem from 29.6 mm (already considering the process of upsetting) to 27.6 mm, creates a 5% reduction of normal stress, 12% of forging load, 30% of the total flash width, 66% of the abrasive wear and 14% of the raw material, according to Tab. 5.1. Thus, the decrease in diameter in addition to increasing productivity by increasing the useful die life of the tools can also generate profitability by reducing raw material.

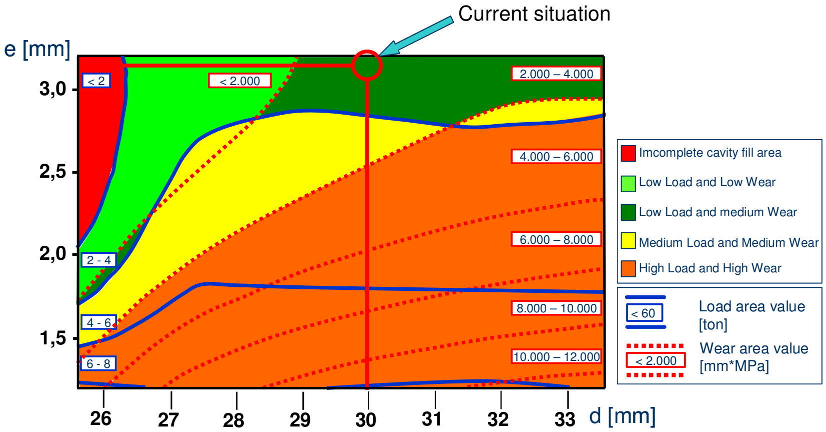

Figure 5.8. Optimization process map, Initial workpiece diameter vs. Flash thickness.

Table 5.1. Workpiece initial diameter versus Flash thickness values.

Workpiece Diameter [mm]	Flash thickness [mm]	Forging Load [10^4 N]	Wear [MPa*mm]	Normal Stress [MPa]	Flash total width [mm]
27,6	3,2	3,3481	878,825	-620,866	54,0058
29,6	3,2	3,7974	2513,67	-653,816	76,6152

6. CONCLUSIONS

It can be concluded that the parameters that most influence the process of abrasive wear are those that affect the internal cavity volume or the initial volume of the workpiece. On both, there is a decrease in the total volume of flash (or burr) and smaller quantities of material leaving the flash land, which produces smaller tangential velocity and smaller dead zones of flow.

The process of upsetting at the stem region during the forging of connecting rods must be taken into account, because the variation of the initial volume in the central region of the workpiece also affect the time the cavity is filled, the final process of wear and the full width of flash. However the decrease in diameter should be considered for the process as a whole, there may appear defective areas in the region of transition from stem to the head of the workpiece which after are going to form the eyes of the rods.

The study should be examined through numerical simulations of the rod as a whole, leading finally to a harder process and spending more time with simulations. However a decrease in the diameter of the workpiece could save raw materials leading the final forged product to a price reduction.

Finally, it is concluded that the analysis of die wear is a slow process and it should be kept in mind all the mechanisms for a better understanding of the tools degradation.

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