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A method for setting variables in Super Plastic Forming process

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ABSTRACT

Purpose: Superplastic forming (SPF) technology exceeds the limit of standard presswork either of form or of thickness distribution, but the lead time and the energy expenditure are more onerous for industrial use. The aim of this work is to study the role that process parameters play in a superplastic forming manufacturing in order to minimize the processing times and the cost respecting the "total quality" of the finished product.
Design/methodology/approach: Identified the basic parameters of SPF process that is the thickness of blank, the strain rate and the processing temperature, were chosen three different values for each of them. For each combination of parameters and using finite element software, a forming simulation of a sample part was made. Important parameters as thickness reduction, stress distribution, time/working pressure curve are calculated and evaluated.
Findings: The obtained results were manipulated in order to create some global indicators that was analysed to study the reliance on process quality and production costs.
Research limitations/implications: The other and more difficult to define parameters, such as cast and initial sheet shape, friction between cast and sheet, need to be evacuated because they also affect the optimisation process, as well as its affordability, that is the result of careful control of process variables.
Practical implications: The highlighted dependencies are whatever useful, during process configuration, to drive production choices for quality improvement and cost reduction of superplastic formed components.
Originality/value: The interesting result is that some dependencies are not as strong as expected from literature. As an example, the quality parameters dependence on the strain rate is no linear. So much as to the decrease of strain rate some indices worsen considerably.
Keywords: Plastic forming; Superplastic materials; Numerical techniques

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1. Introduction

Superplastic forming or SPF is a technique of presswork high temperature of metal sheets that falls in hot blow forming processes. The elongation obtained with this technology exceeds 100% and limits on obtainable forms in a unique forming process is very low (Fig. 1 is an eloquent example). The mechanical characteristics of the finished product are very good, because the hardening of material is practically absent and spring-back is zero, with benefit of obtained dimensional accuracy. The surface finish is excellent, so there is no need to make finish operations. Furthermore, light alloys can be formed with this technology without problems of obtainable geometries. Indeed, in the aerospace industry, the superplastic forming has been used for thirty years.

On the other hand, the forming process is very costly: the working temperatures are very high (approximately 60% of melting temperature), the average size of grains must be less than 10 µm and the strain rates must be less than 10^{-2} s^{-1}. Materials with small size of grains are costly because they require very expensive treatment in terms of energy and time [1]. Furthermore, limited strain rates would make the lead times very long, therefore unacceptable in modern industrial mass productions [2, 3].

Fig. 1. Aerospace part realized with SPF

To assess the possibility of making a component with SPF technology, it is necessary to take into account both technological and economic factors. Numerous works have separately studied some of these factors with numerical simulations or with experiments.

For example: Naka and others have studied, with physical tests, the effects of temperature and forming speed on the forming limit diagram for type 5083 aluminum alloy sheet [4]. Whereas Taleff and the others have simulated bulge forming experiments on blanks with two different fine grained AA5083 sheet materials at two temperatures and they have studied the rupture limit and the forming time [5]. Luckey and the others have simulated and validated a two stage SPF, showing how the thickness profile improves at this technology [6].

A preliminary estimate of "performance" of a super plastic forming process, help to decide if this type of technology is the best suited to the needs, both of project that of market, while optimising the process is fundamental in the modern industry.

Many research papers suggest SPF process evaluations, but proposed considerations are difficult to compare because of deeply different methods, case studies and results used in each simulation or experimentation.

In this paper, starting from a careful analysis on super plasticity phenomenology and process, a set of indexes is proposed to evaluate performances of SPF on a product. These indexes can be evaluated by numerical simulations and must be statistically combined. In particular we emphasize analysis of the influence of process variables by indexes on the most important production requirements.

2. Superplasticity phenomenon

The parameters to be monitored during a SPF process depend on the physical phenomena that underlie this technology. They are the grain boundary sliding (GBS), the dislocation creep (DC) and the grain boundary diffusion (GBD) [7-9]. The relative weight of each phenomenon, still being an object of study, depends on the average size of grains, the processing temperature, the strain rate and the processing pressure.

With GBS phenomenon, the grains, under certain conditions of temperature and pressure, taking a shape less hard-edged that allows the relative sliding [10-12]. This is macroscopically highlighted with great plastic deformations. This phenomenon manifested appreciably only if the average size of grains is less than 10 µm.

With the mechanism of DC there is a dislocation movement of the lattice of metallic material [13]. This gives rise to plastic deformations of the lattice and consequently of all material.

In GBD the atoms migrate from the regions tablets at those less stressed, to reduce the free energy of the system.

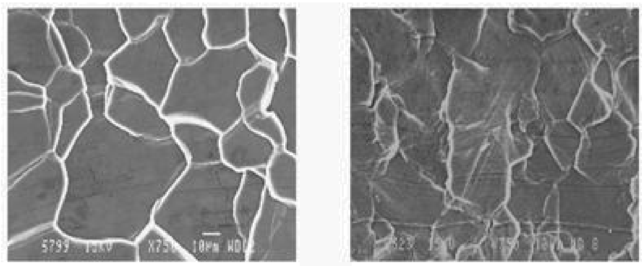

Fig. 2. Grains size change before and after SPF

The microscopic pictures of Fig. 2 shows as the boundary of grains are changed and as the grains slide following a process of superplastic forming at 700K on an aluminum alloy [14].

2.1. SPF mathematical model

The Backofen formula, that is the most commonly used equation in Finite Element simulations of *superplastic forming*, join equivalent stress to strain rate [15, 16]:

$$\sigma = K \dot{\varepsilon}^{m} \varepsilon^{n} \qquad (1)$$

K constant
m strain rate sensitivity coefficient
n coefficient

The *m* coefficient increases with a strain rate up to maximum, then, decreases for higher values, as we can observe in Fig. 3. This coefficient supplies information about thickness distribution on formed blank because it represents also the elongation capacity of material [17, 18].

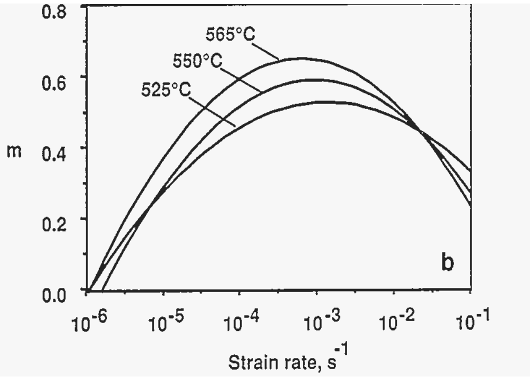

Fig. 3. Strain rate - *m* coefficient as the temperature change on experimental relation for Al5083 aluminium alloy

2.2. Blanks thinning and break

Maxim lengthening achievable by SPF is limited by material breaks where larger thinning and deformation appears [19].

Blank break happens because of a set of molecular and atomic phenomena generally called cavitation [20, 21]. Even if it is difficult to understand the exact behaviour of material during cavitation, behaviour we know the primary causes:

- sliding intersection of grains with a phase without their deformation
- *grain boundary sliding*
- presence of impurities inside the metallic microstructure
- around grains vacuum aggregation

Cavities, developed during forming inside machined material, joined together with them, already present and grow (*coalescence*). Consequently, we have reduced structural resistant section and increased internal stresses, up to break of blank (Fig. 4).

The cavitation is composed of three main phases: *nucleation*, *growth of voids* and *coalescence*. The most critical phase is *growth of voids* since it is very hard to model its development then it is difficult its control [22, 23].

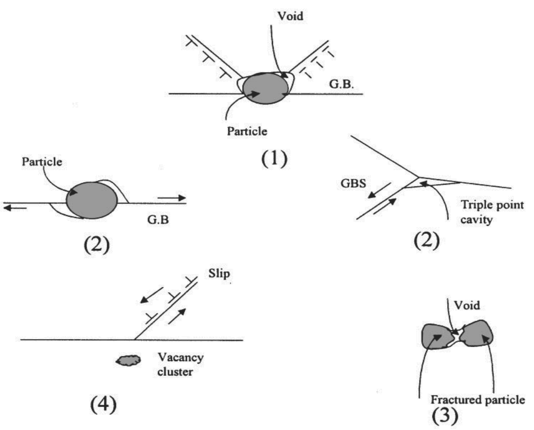

Fig. 4. *Coalescence* phenomenon

Main mathematical models describing the *growth of voids* during superplastic deformation are based on fixed plastic flow theories and can be basically classified as:

- *diffusion* (DIF) *controlled growth*
- *plasticity* (PLA) *controlled growth*
- *plasticity diffusion* (SPD) *controlled*

Total cavitation can be computed as sum of all three contributions which relative relevance depends on forming parameters.

$$C_{V_{TOT}} = C_{V_{PLA}} + C_{V_{DIF}} + C_{V_{SPD}} \tag{2}$$

Working temperature, strain rate, initial grains size and final deformation level before break are the main influencing parameters on cavitation evolution during forming

Considering reputedly constant grains size it can makes some assertions.

Density and average dimension and volume fraction of cavities decreases with temperature or strain rate increment. An initial cavities density rising follows deformation growing up to a material dependent value with subsequent density saturation, while average dimension and volume fraction of cavities ever increase. When cavities dimension grows, then atomic diffusion decreases, plastic dislocation increases and cavities shape extends along stretching direction [24].

3. Process variables

Super Plastic Forming process goes through many steps by a hot forming inflating gas press: the blank, loaded on press and fixed by plates equipped with warmers, and the die was pre-heated up to about 1000°C.

Once the super-plastic temperature condition was reached, a gas was inflated according to a pressure curve, so that the blank will be completely pushed against the die. After forming, die and formed blank will be cooled so that the blank can be pulled out. Right materials to be *superplastically formed* mostly are aluminium, titanium and magnesium alloy. Blank thickness depends on the final shape, press power and production lot.

Design and technological conditions influence production choices: design conditions refer to product and can be related to weight limit, maximum allowed stresses, material cost, product life-cycle, strength, etc; technological conditions refer to production systems and can be related to maximum reachable pressure, maximum press power, numerousness scraps, production time and cost, etc.

3.1. Temperature

Depending on used material, a specific temperature value activates and balance *grain boundary sliding* and *diffusion* and *dislocation creep* phenomenon relevance.

High working temperature increases the GBS contribution to final elongation and reduces the strain hardening phenomenon so mechanical characteristics of product improve [25].

Not uniform temperature distribution on blank can improve thinning distribution: higher thinning occurs in the last formed areas because of reduced material contribution from other already formed areas. Already formed area contribution can be improved with locally increased temperature in order to raise material flow and to uniform thickness.

Unfortunately, high working temperature brings atomic and molecular phenomenon like rising grain size that contrasts plastic deformation.

Contribution of *diffusion controlled growth*, *plasticity controlled growth* and *plasticity diffusion growth* on damage by cavitation effects is another effect of working temperature because distribution and average dimension of vacuums, then mechanical properties of product, depends on their relative distribution. As general rule we can assert that damage level decreases when temperature increases.

Finally, higher forming temperature level weighs on finished product and plant costs. Life time of dies and presses decrease with higher stresses induced by higher working temperatures and dies, therefore, presses requires better mechanical characteristics and much expensive material alloy.

Besides, substantial expenditure of energy is needed to set up and keep die, blank and plates to the right temperature during all the long working time

3.2. Pressure cycle

In order to obtain a constant strain rate during deformation, forming pressure must vary continuously in time. In particular pressure must increase with time because extending contact surface between blank and die material flow and strain rate reduce.

Likewise temperature, strain rate affect activation and influence percentage of the three flow phenomenon and, again like temperature, Backofen sensitivity coefficient *m* changes.

To be more precise, when strain rate increases, then *grain boundary sliding* contribution decreases in respect to *dislocation creep* contribution causing increasing material strain hardening and worse mechanical properties of pressed product.

In fixed- temperature condition and inside a certain strain rate range, the *m* coefficient first grows with strain rate up to a max value then decreases.

Density and vacuum average dimensions depend on predominant damage typology and because, if all other conditions are equal, the cavitation depends on strain rate values therefore, as for temperature, they also depend on strain rate value. In the large, Pressure curve choice and consequent max strain rate obviously affect forming time then working time and production capacity. seriousness of cavitation grows with strain rate (Fig. 5).

3.3. Die

Based on dynamics of blank to die approaching, it is possible to estimate final thickness distribution because the last formed zone presents the bigger thinning even if die shape is very important in this case.

The most important shape parameter is a radius that affects thinning and breaks. For example a small radius at the top of die obstructs material flow towards the centre of blank then they reduce superplastic effects.

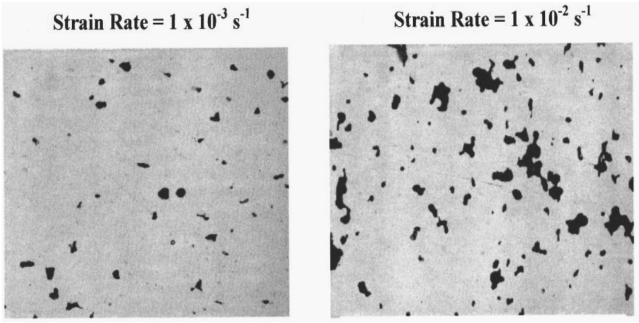

Fig. 5. Cavitation after Tensile Test on aluminium alloy specimens at fixed-temperature and different strain rate conditions

Also, much deeper dies and complex geometric shapes reduce material flow and increases global thinning and thinning distribution.

Also lubrication, used to help sliding between a blank and die, affect friction and then it influences thinning distribution and modulus and cavity phenomenon from friction force level during presswork influence not only on material flow but also plasticity typologies prevalence. In general, high friction coefficient generates a non-homogenous thickness distribution and high friction force increases cavitation phenomenon.

4. Analysis of SPF process variables

The process parameters that "influence" the final product are:

- temperature
- pressure cycle
- structure and geometry of the die
- thickness of blank
- lubrication

Among these we consider temperature, thickness of blank and strain rate, the latter directly related to the pressure cycle that is evaluated as FE simulation result, because they generally affect any manufacture process. Lubrication and structure of the die were not considered because their influence is related to the particular shape that you want to get. The pressure cycle is a FE result of simulation.

To evaluate the good properties of this type of manufacturing, it is necessary to consider the following aspects:

- thickness distribution
- maximum thinning
- evolution of cavitation
- forming time
- actual cost of manufacturing

The first three parameters have valence for mechanical properties of finished product such as stiffness, static and fatigue strength.

The forming time is closely related with feasibility of the process because excessive time of manufacturing may be unacceptable from an economic, technological and commercial standpoint.

Finally, the actual cost of manufacturing is the sum of the energy cost, cost of equipment and the not negligible cost of material.

As indicators of mechanical properties of the finite product were considered the maximum thinning, the thinning distribution and the distance from the breaks limit, while economic and technological indicators had been considered as the forming time, the maximum pressure and energy of pressure is necessary for the manufacturing.

4.1. FE simulation

The simulation was made on a rectangular die with a centred cavity of depth 100mm. The external dimensions of die are 810mmX460mm, while the dimensions of cavity are the following 600mmX200mm. The radii of curvature of the die are very large in order to be released from factors. The blank has the same external dimensions of the die.

Because of the symmetry of the problem, the simulations were performed on a fourth of the model. The blank was modelled with shell elements of square form of the following dimension 5mm, while the die was modelled with a coarse mesh, because it is considered as a rigid body. Fig. 6 shows the models both of the die than of the blank.

The simulations were done with the explicit finite element software (*LSDYNA970)* that provides specific commands and material cards for the superplastic forming and then control the pressure level to limit the max strain rate [26-28].

The material of the blank is Al5083 whose characteristic constants, to vary of temperature and strain rate, were taken from literature. The lubricant, interposed between die and blank, contains boron nitride with a coefficient of friction μ=0.16.

They were performed twenty-seven simulations obtained by the combination three temperature values, three values of strain rate and three values of thickness [29] (Table 1, Fig. 7).

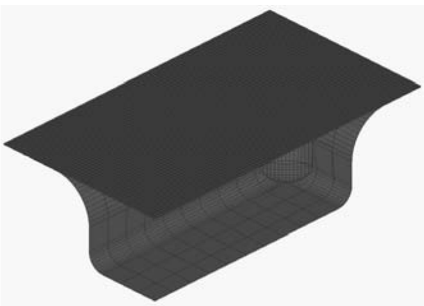

Fig. 6. FE model of a quarter of die and blank

Table 1.
Result of the thickness reduction obtained by simulation for the T1Sp2V3 configuration.

Temperature	Thickness	Strain Rate
T_1=525°C	Sp_1=1.0mm	$V_1=2.5*10^{-3}s^{-1}$
T_2=550°C	Sp_2=1.5mm	$V_2=5.0*10^{-3}s^{-1}$
T_3=565°C	Sp_3=2.0mm	$V_3=7.5*10^{-3}s^{-1}$

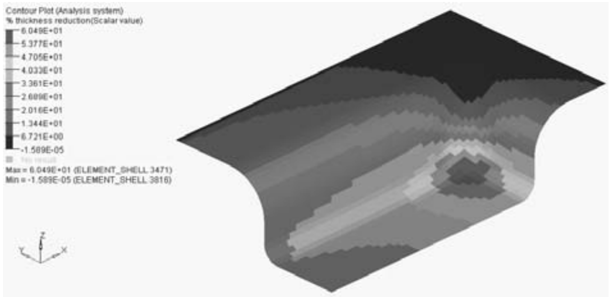

Fig. 7. Case T1Sp2V3: thickness reduction

4.2. Evaluation indexes

The **maximum thinning percentage** (***mtp***) and the **time of forming** (***ft***) are output of simulation, while the others check indexes were obtained elaborating the results of calculations. In particular the pressure cycles, function of the time, were obtained with a fourth grade polynomial approximation of pressure values resulting from the simulation. This was done to eliminate the sharp fluctuations of the values, always present in mathematical simulation. These cycles were extracted to the pressure peaks (***pp***), expressed in MPa, and the energy of pressure (***pe***), estimated with the integral of the curves and then expressed in MPa*s. In the Fig. 8 both the values of the pressure, obtained from tests, and the polynomial approximation of the same are reported, all functions of time and for the T1Sp2V1 configuration.

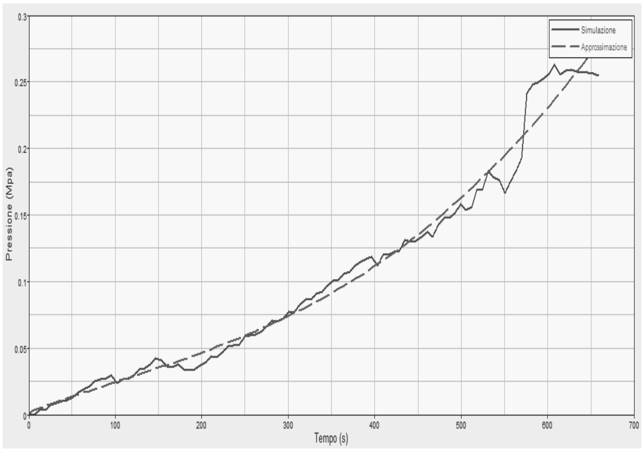

Fig. 8. Numeric (continue line) and filtered (dashed line) pressure curve

The **thickness distribution** (***td***) was estimated with an index thus defined: simulation was extrapolated to the elements number of blank mesh what have suffered a reduction of thickness bigger by 40%, this number was divided for the total number of elements shell and then multiplied by a 100 factor so as to obtain a percentage value. If, at varying process parameter, this index increases it means that regions, with a reduction of thickness, greater that the predetermined, is of greater extension and then they contribute at final deformation given by several areas of material. This value has the meaning of volumetric fraction because the initial dimension of elements are homogenous and also because the simulation software requires, unless otherwise specified, the constancy of volume.

For the **distance from limit of break of the material in the region most deformed** (***bkl***) was thought to be an index based on simplified model of maximum deformation obtainable from SPF. This model calculated the limit elongation as a logarithmic function of coefficients *m* and *n*. In short the maximum values of plastic deformation resulting from the simulations were divided by the rupture limit of model and subsequently made of the complement to one. The final result has expressed percentage so as to have a measure of the range remaining of deformation.

Table 2 shows the result of twenty-seven simulations, carried out as specified above. The combinations were expressed by written symbols of three values of the process variables.

Table 2.
Calculated *mtp*, *td*, *pp*, *pe*, *bkl*, *ft* indexes values

	mtp	*td*	*pp*	*pe*	*bkl*	*ft*
T1Sp1V1	59.08	7.27	0.172	31.56	54.96	525
T1Sp1V2	59.37	7.30	0.287	26.21	52.39	276
T1Sp1V3	60.40	7.57	0.392	24.97	47.50	143
T1Sp2V1	59.12	7.43	0.279	68.25	53.69	574
T1Sp2V2	59.59	7.33	0.545	45.23	51.05	295
T1Sp2V3	60.49	7.70	0.532	38.73	46.26	154
T1Sp3V1	59.56	7.62	0.322	73.02	52.06	613
T1Sp3V2	59.94	7.43	0.850	98.05	49.20	314
T1Sp3V3	60.43	7.73	1.186	55.22	44.65	159
T2Sp1V1	58.10	6.90	0.164	30.08	59.97	481
T2Sp1V2	57.39	6.57	0.216	19.60	62.54	193
T2Sp1V3	58.41	6.92	0.355	21.44	57.98	135
T2Sp2V1	58.13	7.03	0.299	51.21	58.67	565
T2Sp2V2	57.52	6.60	0.381	32.73	61.46	274
T2Sp2V3	58.53	6.98	0.497	33.61	56.71	145
T2Sp3V1	58.36	7.17	0.280	67.29	57.37	604
T2Sp3V2	57.80	6.68	0.645	48.60	60.05	299
T2Sp3V3	58.56	7.06	0.934	51.66	55.39	153
T3Sp1V1	55.57	5.96	0.100	15.70	68.96	465
T3Sp1V2	55.93	5.98	0.250	18.53	67.33	233
T3Sp1V3	57.31	6.55	0.254	15.57	62.62	130
T3Sp2V1	55.00	6.09	0.103	22.55	69.03	514
T3Sp2V2	56.10	6.06	0.378	27.86	66.39	207
T3Sp2V3	57.35	6.63	0.397	25.47	61.38	143
T3Sp3V1	55.45	6.28	0.129	30.92	67.87	559
T3Sp3V2	56.37	6.17	0.348	30.92	65.26	223
T3Sp3V3	57.61	6.66	0.646	37.56	60.01	150

4.3. Indexes analysis

To find out the dependence between quality indexes and process parameters a Taguchi approach was used [30, 31]. In particular the value of control parameter, relative at a value of process parameter, is the mean of all cases value is present. Figures 9, 10, 11, 12, 13, 14 show the total results.

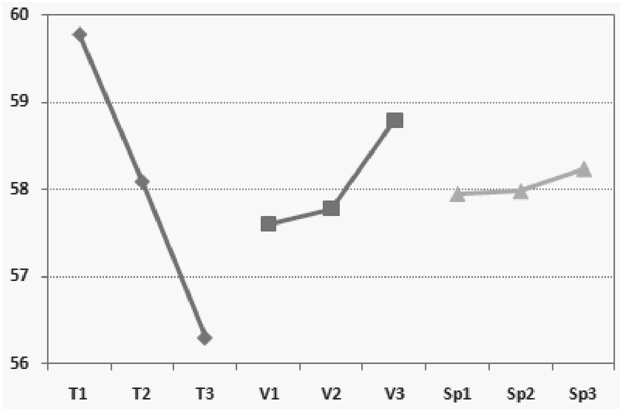

Fig. 9. Trend analysis of ***mtp*** index over Temperature (T), Strain Rate (V) and Thickness (Sp)

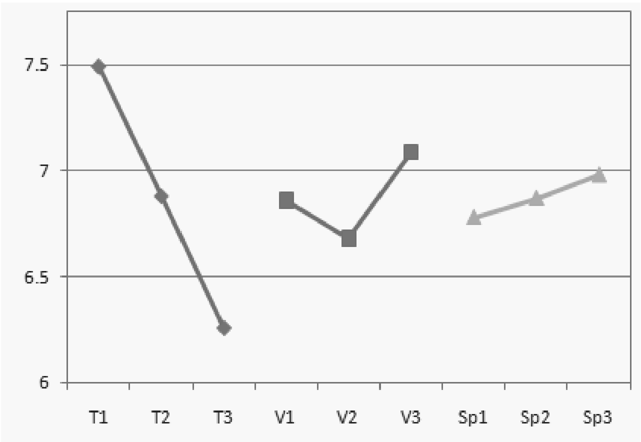

Fig. 10. Trend analysis of ***td*** index over Temperature (T), Strain Rate (V) and Thickness (Sp)

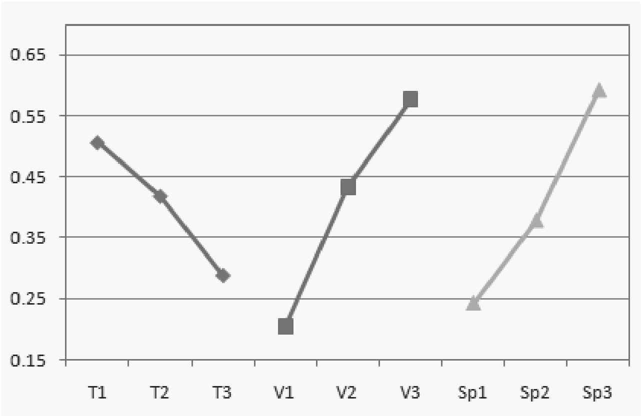

Fig. 11. Trend analysis of ***pp*** index over Temperature (T), Strain Rate (V) and Thickness (Sp)

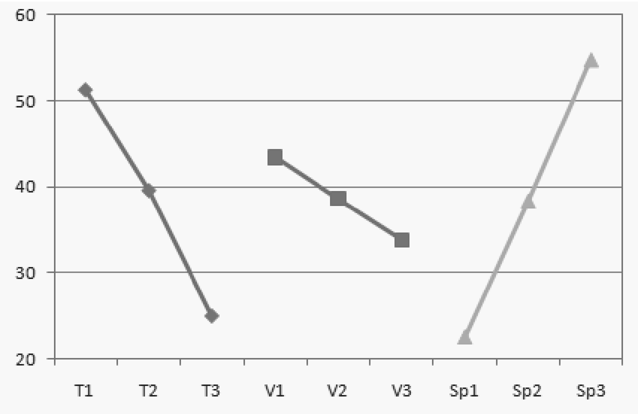

Fig. 12. Trend analysis of ***pe*** index over Temperature (T), Strain Rate (V) and Thickness (Sp)

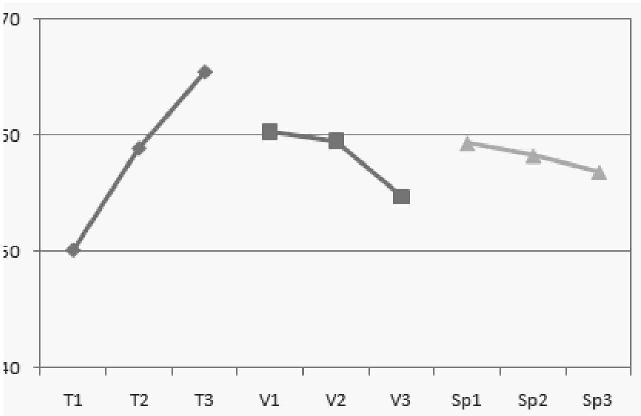

Fig. 13. Trend analysis of ***bkl*** index over Temperature (T), Strain Rate (V) and Thickness (Sp)

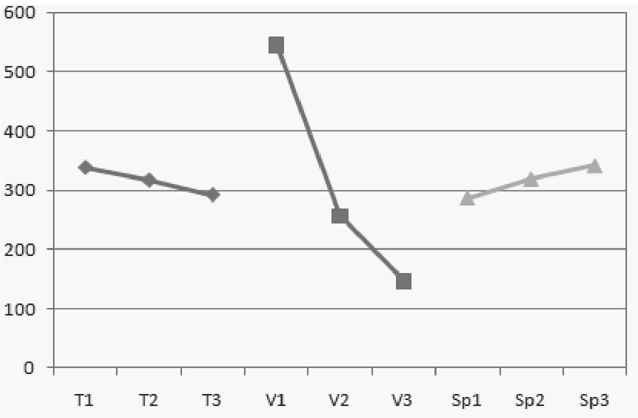

Fig. 14. Trend analysis of ***ft*** index over Temperature (T), Strain Rate (V) and Thickness (Sp)

For an overall and more purposeful vision, on the same graphic all three dependences were reported.

From an examination of the graphs immediately the qualitative dependences emerged between all control indexes and three process variables.

In particular, the maximum thinning decreases rapidly and linearly with increasing temperature while the trend is inverse and non linear at strain rate. Finally the maximum thinning is not very influenced by the thickness of sheet metal although the slope of the line tends to grow between Sp2 and Sp3, assuming that for greater thicknesses the phenomenon is amplified.

Also the index of the distribution of thinning is very sensitive to temperature changes. The trend is linear and inversely proportional to the temperature, and therefore, the distribution of thickness worsens. Instead this index has a minimum at strain rate V2 and therefore for lower or upper values the distribution of thinning improves. The distribution of thinning, however, is not very sensitive to the thickness variation.

The pressure peak is very sensitive to strain rate and thickness and is directly proportional to both parameters. The max pressure is moderately sensitive to the increase of temperature and the dependency type is inversely proportional.

The index for estimating the energy of pressure increases significantly with increasing thickness, while it decreases along with increasing temperature. Also this index increases with increasing the strain rate, but slowly.

The rupture index that estimates the entity of cavitation, decreases appreciably with increasing the temperature, while it's less sensitive both to the strain rate and to the thickness. The dependence is proportionally inverse.

Finally, the time of forming is proportionally inverse to the strain rate and, above all, the time of forming decrease slightly both with the reduction of the thickness and the increase of temperature.

By the results obtained it would appear that the increase of both temperatures is always positive, but it is not. In fact the increase of temperature makes the material softer, create problems of sliding and bonding.

5. Conclusions

Superplastic forming (SP) technology exceeds the limit of standard presswork either of form or of thickness distribution, but the lead time and the energy expenditure are more onerous for industrial use. Process variables must be carefully selected to grant product workability and industrial attractiveness.

From results obtained by numerical simulation on a SPF case study, some global indicators can be obtained that allow to evaluate process quality and production costs.

Another important result is that some dependencies are not as strong as expected from literature. As an example, the quality parameters dependence on the strain rate is not linear. So much as to the decrease of strain rate some indices worsen considerably.

The work shows therefore how main superplastic forming process variables influence the finished product. The next step in the future would be to study both effects of the form factors and lubrication.

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