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SYSTEMATIC PROCESS SELECTION FOR COLD FORGING

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ABSTRACT.

This paper presents a hybrid model for determining feasible cold forging methods for individual components that is extendable to other manufacturing areas. An initial screening of candidate processes could potentially be followed by a systematic comparison of their capabilities through fuzzy sets and the product's functional requirements. A comparative complexity evaluation between the component and a Near Net Shape (NNS) approximation formed product allows evaluation of the further effort necessary to produce the final component. The model supports the possibility of redesign by means of an iterative procedure in order to assess different cold forging processes with different designs. After presentation of the methodology the paper end with a case study application that ranks feasible combinations of process for a given design. This illustrates both the strengths and limitations of the proposed approach.

1. INTRODUCTION

Process selection is a crucial step in the early stages of any product or component design. However in the initial stages of any new design its characteristics are hazy and uncertain. A similar situation occurs when considering the possibilities of adopting innovative manufacturing methods or implementing incremental changes to established products; always the selection of design-process-material combination is challenging and rarely optimized. In this context the adoption of new near net shape (NNS) manufacturing technologies could dramatically impact on the economics of components by reducing or even eliminating waste and machining operations by transforming raw stock materials to good approximations of the final shape in a few steps. Consequently evaluating cold forging opportunities and their applicability to new and existing product designs is critical however despite this importance notion of formability are not easily expressed in an objective manner. All too often descriptions are subjective (e.g. "largely cylindrical", "relatively shallow", "moderate stain hardening").

Aware of these problems researchers over the last twenty years have attempted to define systematic process selection methods for individual products. Systems have been reported where criteria such as product costing, complexity and fuzzy sets based compatibility have been used as criteria for identifying and comparing viable manufacturing processes given the geometry, material, production quantities and value of components. Individually each reported method has strengths frequently balanced by critical weakness, arising from the particular field of application that lead to neglect some forming bases perspectives. For example, Swift's seminal costing model (Swift & Booker 2013) has a broad vision of manufacturing processes, but is too high level for identification of specific processes (e.g. 'cold forming vs casting' not 'flow forming vs rotary forging'). Furthermore huge amounts of process specific data would be required before the methodology could be adapted in scope to specific processes within a general classification.

Manufacturing complexity is the physical ability of a manufacturing process to perform one or more feature-generating operations to some level of accuracy and precisions (Algeo, 1994). Manufacturing process capabilities are determined by manufacturing resource factors, work part material and geometry factor (Giachetti 1998). Generally, producing near boundaries of process capabilities require more effort than in their usual range. Compatibility is a measure of how process is able to produce this features and with how much effort. Compatibility ranking is measure of how processes are suitable for a given product and specification. Product complexity evaluation is a most detailed approach that investigates directly design and requirements, matching them with process capabilities. The idea of this paper is to summarize in a single approach both the methodologies, including application of NNS philosophy, which includes a process selection for minimizing resources' waste.

2. HYBRID PROCESS SELECTION METHODOLOGY

Selection methodology concerns cold forging and forming processes. Each have been considered as final step of manufacturing chain. Eliminating further steps (machining) and reducing primary shaping processes are main aims of NNS approach. Preform manufacturing and design has been not considered in this investigation, even if it has an important impact on raw material saving and process design. Figure 1 summarizes the designed methodology steps.

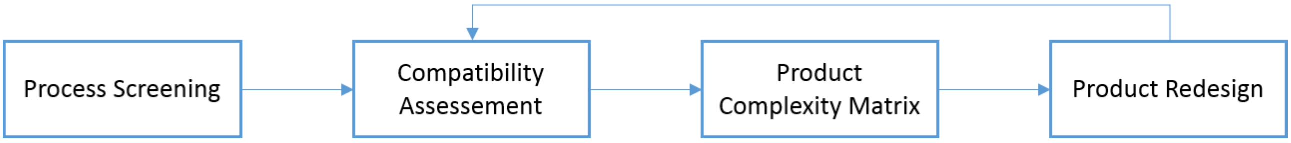

Figure 1: Fuzzy set for process capabilities (adapted from (Ravi 2005).

- Process screening: priory filtering unmatchable processes.
- Compatibility assessing: ranking processes through fuzzy sets, describing process manufacturing capabilities and product requirements.
- Product Complexity calculation: evaluating all product features through complexity matrix, for every process application.
- Redesign loop: review product features and requirements, in order to improve quality, manufacturing compatibility and reduce process complexity.

Material selection has been not included in this investigation. Thus, material is a fixed parameter in the analysis. Although not always the case, this is an appropriate assumption in the context paper's case study application (valve seat), in which corrosion and corrosion fatigue behavior have been detected as most common failure causes. Improvement in mechanical proprieties is not directly proportional to an improvement in corrosion behavior, so material choice has been left as an

2.1. Process Screening Matrix

The degree of correspondences between a product requirement and a process's characteristics is used to reduce the number of candidate processes. Process capabilities considered for this scope are production volume, feasible shapes, maximum workable weight, maximum and minimum workable section/wall thickness, workable materials and lead-time. These features are clearly able to detect if some processes are infeasible for the targeted product, regardless of any incremental improvement in their capabilities. Matching between these processes features and product characteristic is able to severely cut down the number of process being considered (e.g. Incremental Sheet Forming cannot satisfy an high production volume or open-die forging cannot be considered as final step for a complex geometry). This approach is widely used in literature for a first process selection, as in Swift & Booker (2013), Schey (1999), Altan & Ngaile (2005) and many others. This logic has been applied as in Table 1.

2.2. Fuzzy Logic – Compatibility Assessing

Fuzzy logic is an artificial intelligence technology that is gaining in popularity and applications in control systems and pattern recognition. It is based on the observation that people make decisions based on imprecise and numerical information (Daws et al. 2008).

Fuzzy models, or sets, are mathematical means of representing vagueness and imprecise information, hence the term fuzzy (Kalpakjian & Schimd 2009). Differently from traditional probability, fuzzy sets are capable of represent on, use and manipulate of data that has a range of values, due to their uncertainness. Hence in fuzzy logic, distinction between from full compatibility (one) and incompatibility (zero) is gradual between extreme ranges of the fuzzy set. Figure 2 illustrates the fuzzy logic approach. Several authors applied slightly different versions of fuzzy approach to process selection and decision making in manufacturing (Giachetti 1998; Esawi & Ashby 1998; Ravi 2005; Daws et al. 2008). Where, $L_{min-abs}$ is the absolute minimum value, L_{min} is the minimum typical, L_{max} is the typical maximum value, $L_{max-abs}$ is the absolute maximum value of the investigated process's feature. L_{req} is the requested value of product feature (e.g.

required surface roughness). Compatibility assessment can be performed by mapping from qualitative description (‘low’, ‘low to medium’, ‘medium’, ‘medium to high’ and ‘high’) to numerical values.

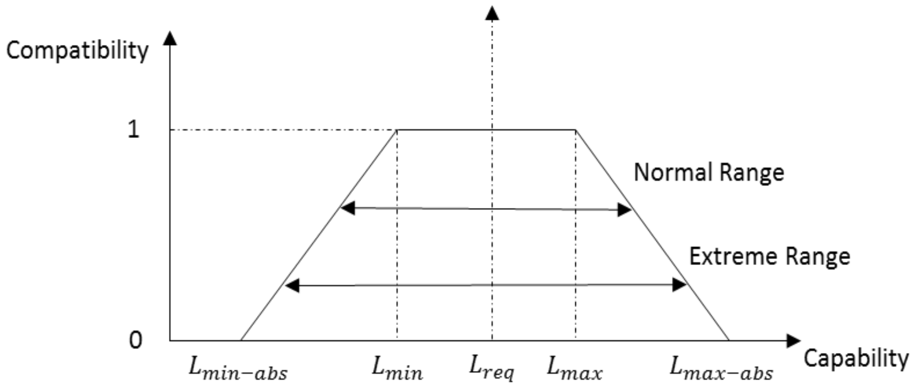

Figure 2: Fuzzy set for process capabilities (adapted from (Ravi 2005).

As in Ravi (2005) and later in Daws et al. (2008), compatibility is defined by the requested value and the defined four values of the fuzzy set. If the requested value is outside of the set (4), compatibility is considered null. If it is in normal range, then the request is fully compatible (1). If value falls between normal and extreme ranges, then the value is intermediate between 0 and 1, defined by a linear behavior (2,3).

$$P_{Lreq} = 1, \; if \; L_{min} < L_{req} < L_{max} \tag{1}$$

$$P_{Lreq} = \frac{(L_{req} - L_{min-abs})}{(L_{min} - L_{min-abs})}, \; if \; L_{min-abs} < L_{req} < L_{min} \tag{2}$$

$$P_{Lreq} = \frac{(L_{max-abs} - L_{req})}{(L_{max-abs} - L_{max})} if \; if \; L_{max} < L_{req} < L_{max-abs} \tag{3}$$

$$P_{Lreq} = 0, \; if \; L_{req} < L_{min-abs} \, , or \; L_{req} > L_{max-abs} \tag{4}$$

Approach of Giachetti (1998) defines two different cases that occur in compatibility evaluation. Using Dubois and Prade (1988) possibility theory, possibility and necessity are defined for every feature. Possibility assesses to what extent a feature satisfies the request (optimistic selection strategy), on the other hand, necessity expresses to what extent a features certainly satisfies the query. It is measure through a pessimistic selection strategy by measuring the impossibility of the opposite event. This opposite event is determined using the complement of the event. Figure 3 shows how to perform the calculations, in agreement with previous definition, although it refers to a variable request. In order to evaluate possibility and necessity in a unique compatibility number, Giachetti (1998) use a factor β called that represent the level of optimisms or pessimism of the decision maker. Factor β is 1 for an optimist decision maker and 0 for a negative one, but always included in the interval $\beta \in (0,1)$.

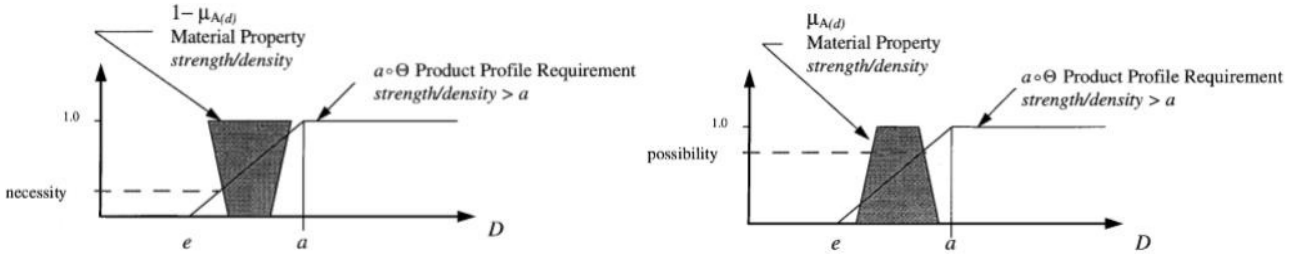

Figure 3: Possibility measure (left) and Necessity measure (right) under a variable requirement (Giachetti 1998).

A weighted average is calculated for each requirements between possibility and necessity values, mediated by factor β (possibility) and $1 - \beta$ (necessity). Using this methodology, a compatibility measure has been assigned to every process/product selection features. A geometric weighted mean is used for aggregating all $n - th$ compatibilities values (5). Weight (*w*) is assigned to every feature using linguistic values. Each of them is calculated as in equation (6). This methodology has been used for the case of study and displayed in Table 2.

$$P\left(L_{req_1}, L_{req_2}, \dots, \dots, L_{req_n}\right) = \prod_{i=1}^{n} P(L_{req_i})^{r^i} \tag{5}$$

$$r = w_i / \sum_{i=1}^{n} w_i \tag{6}$$

In conclusion, fuzzy logic is capable of ranking the candidate processes and ordering them by features compatibility with requested ones. Usually this features include technological and other quantifiable requirements (e.g. tolerances, surface roughness), although it can be easily extended to every required feature (e.g. material usage, labor cost). The compatibilities values are sorted into an ordered list and a threshold applied for assessing the most compatible processes and discarding the others.

2.3. Complexity Models - Product Complexity Matrix

Product complexity influences directly the process complexity, so an effective understanding of complexity nature and its relative measure can directly connect them. Product complexity increases with the number and diversity of "features" to be manufactured, as well as the nature and difficulty of the tasks required to produce the features (ElMaraghy & Urbanic 2003). Cooper et al. (1992) have measured product complexity as a volume weighted average, meanwhile Guenov (2002) has used entropy for the information number evaluation. ElMaraghy & Urbanic (2003) developed a complete formula for evaluating the product complexity (7).

$$CI_{product} = \left(D_{R_{product}} + c_{f_{product}}\right) \mathrm{H}_{\mathrm{product}} \tag{7}$$

Where, $\mathrm{H}_{\mathrm{product}}$ is the information entropy measure (8), $D_{R_{product}}$ is uniquess/diversity information measure (9) and $c_{f_{product}}$ is the relative complexity coefficient. The following equations define the three contributors to product complexity used in this paper.

$$\mathrm{H}_{\mathrm{product}} = \log_2(N+1) \tag{8}$$

$$D_{R_{product}} = \frac{n}{N} \tag{9}$$

$$c_{f_{product}} = \sum_{f=1}^{F} x_f c_{f,feature} \tag{10}$$

Where: N, total quantity of information; n, quantity of unique information; c_f, feature complexity coefficient (10); x_f, percentage of dissimilar features.

A matrix methodology is used to determine the relative complexity coefficient (ElMaraghy & Urbanic 2003). Complexity matrix describes all product characteristics and specifications. A factor indicates the relative effort to produce each of them or to perform the related task. Features (*J*) and specification (*K*) are defined and evaluated for every characteristic, assigning them a factor (0 low effort, 0.5 medium effort, 1 high effort). All the factors are incorporated in the feature complexity coefficient (11) and weighted by their percentage of presence in the component (12,13).

$$c_{f,feature} = \frac{F_N F_{CF} + S_N S_{CF}}{F_N + S_N} \tag{11}$$

Where, F_N, is the quantity of features; F_{CF}, is the feature complexity factor; S_N, is the quantity of specifications; S_{CF}, is the specification complexity factor. Table 5, an application of this methodology is used for the case study.

$$F_{CF} = \frac{\sum_{j=1}^{J} factor-level_j}{J} \tag{12}$$

$$S_{CF} = \frac{\sum_{j=1}^{K} factor-level_k}{K} \tag{13}$$

In conclusion, the complexity index (obtained through the correspondent matrix) represents the difficulty of producing the component. A complexity index number does not have any meaning by itself. Comparing processes' complex indexes defines the closest one to the final shape, in terms of less needed manufacturing effort. So, selecting the process with lowest complexity index, from a list of candidate processes, means to adhere to NNS approach (reduction in manufacturing effort). In this sense, the previous threshold's application to fuzzy sets (which reduces the process candidates' number where complexity methodology is applied) is a further step in resources saving direction (limiting it to the most compatibles processes).

2.4. Redesign Loop

Another step in NNS direction is to apply a redesign loop. During complexity and compatibility analysis, product requirements and characteristics have been investigated in depth. Adding knowledge about product failure mechanism and status, changing product design is an automatic step. Modification should improve product quality (e.g. improving tolerances) and simplify its geometry. This changing would reflect on compatibility assessment and complexity factors, showing if modifications would have a positive or negative impact on compatibility and complexity, thus on whole production process.

3. CASE STUDY: VALVE SEAT FOR VOLUMETRIC COMPRESSOR

The considered case study is a valve seat, although commercial confidentiality prevents specific drawings being publish it has a form not unlike the Novatech valve Following processes have been considered: open- and closed-die forgings, injection forming, rotary (orbital) forging, hydroforming, shear and flow forming. All the manufacturing process capabilities and further data have been taken or derived from handbooks and papers (Schey 1999; Altan & Miller 1990; Chou & Roger 1988; Shivpuri 2013; Alaswad et al. 2012; Balendra & Qin 2004; Onodera & Sawai 1992; Siegert et al. 1997).

Process screening has been performed using Table 1. Information about seat valve has been matched with the displayed process capabilities. Design shapes classification refers to Schey's (1999) geometry classification. Unmatchable features are highlighted in red. Hence, hydroforming, shear forming, open-die forging and flow forming have been discarded, because they cannot manufacture the required shape.

Table 1: Process screening table for case study.

Process features	Open - Die	Closed-Die	Precision	Injection	Rotary	Hydro-forming	Shear Forming	Flow Forming
Production Volume	Medium-High	Medium-High	Medium-High	High	High	High	Low-High	Low-High
Design Shapes*	R(1/3),B, T(1/2),F0	R(0/7), B(0/7), S, SS, T (1/4)			R(1/7) T(1/7)	**T(1,6),F(4)**	**T(4) F(4)**	**T(0/2)**
Maximum weight [kg]	150-200	50-150	30-80	20-40	5-10	20-50	30-50	30-50
Maximum Section [mm]	No Limit	No limit	No limit	No limit	80	50	70	75
Minimum Section [mm]	5	3	1	1	0.8	0.6	0.1	0.1
Workable Materials	Al, Mg, Cu, Pb, Sn and Zn Alloys, Carbon Steel (Low) Alloy Steel (low)				Al, Cu, Zn, and Mg Alloys, Carbon Steel (Low), Alloy Steel (Low, High), Ti and Ni Alloys			
Lead-time	Weeks	Weeks	Weeks	Weeks	Days	Weeks	Days	Days

Compatibility assessment has been performed using the formulas in Section 2.2. Several manufacturing capabilities have been selected for determining the compatibility. Radial and axial tolerances have been included as well as surface roughness in order to check critical technological compatibility. Material usage values are not specific to the product being considered but have been take from literature, allow raw material usage to be a factor in total compatibility. Tooling, equipment and labor costs have been defined using qualitative linguistic evaluation (5-high, 1-low). As discussed, four values are needed for describing process capabilities (fuzzy set) and one for product requirements. In Table 2, possibilities, necessities, relative and total compatibilities' values have been displayed for the rotary forging case.

Table 2: Compatibility evaluation though fuzzy sets in rotary forging case.

Rotary Forging Compatibility Assessment	Level absolute min	Level min	Level max	Level absolute max	Request	Possibility	Necessity	Compatibility	Ranked compatibility	Weight (1/5)	Ranked Weight
Radial Tolerance [±mm]	0.02	0.04	0.08	0.15	0.13	0.33	0.67	0.50	0.89	5	0.16
Axial Tolerance [±mm]	0.05	0.10	0.30	0.40	0.25	1	1	1	1.00	4	0.13
Surface Roughness [Ra]	0.10	0.20	0.40	0.80	0.80	0	1	0.5	0.89	5	0.16
Material Usage	0.88	0.90	0.95	0.99	0.90	1	1	1	1.00	5	0.16
Tooling Cost	1	2	3	4	3	1	1	1	1.00	4	0.13
Equipment Cost	3	4	4	5	3	1	1	1	1.00	4	0.13
Labor Cost	1	2	2	3	2	1	1	1	1.00	4	0.13
Optimism Level (β) = 0.5					**Total Compatibility** = 0.80						

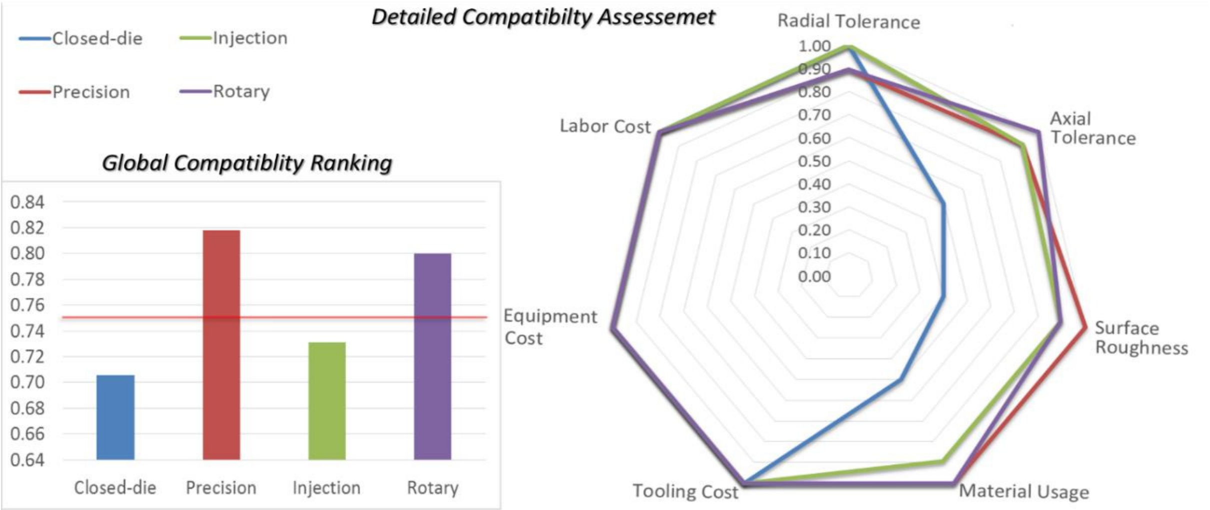

Figure 4: Comparison between open-die, closed-die, injection and rotary forgings' compatibilities for every single feature.

The selected optimism level is 0.5, as suggested by Giachetti (1998). Every parameter has been weighted for its overall contribution to compatibility. Radial tolerance, surface roughness and material usage have been rated as most important. For the first two, main reason is due to valve seat requirements and usage. Latter one is important for adhering to NNS approach. Also if NNS oriented approach has its most important impact on sequent step, (compatibility rank and processes redesign). Thus, costs and material saving should be included in this step. In Figure 4, all relative compatibilities have been showed for the four processes. Also if rotary forging has same or more potentialities than precision forging, its compatibility is lower, due to the product request. Figure 4 illustrates the also global compatibility ranking. As expected, precision and rotary forging have higher compatibility rates than injection and simple closed-die forging. In this case study, the cut-off threshold has been set as 0.75, thus latter two processes have been not considered for complexity evaluation.

Table 3: Valve seat complexity matrix for precision forging.

Precision Forging	Features						
	Number	J=4				SUM	SUM/J
Description		Shape	Geometry	Tolerances	Tolerances Stack Up		
Valve contact surface	1	0	0.5	1	1	2.5	0.625
Internal Surface	1	0.5	0.5	0	0.5	1.5	0.375
External surface	3	0.5	0.5	0.5	0.5	2	0.5
Gauge pos. slot	1	1	1	1	1	4	1
Ring positioning slot	1	1	1	1	1	4	1
Seat support surface	1	0.5	1	1	1	3.5	0.875
Bottom Surface	1	0.5	0.	0.5	0.5	2	0.5

	Specifications							
	Number	K=variable					SUM	SUM/K
Description		Surface Finish	External Fillets	Internal Fillets	No Unfilled Sections	No Surface Cracking		
Valve contact surface	1	0	1	1	0	0.5	2.5	0.5
Internal Surface	1	0.5		0	0.5	1	2	0.5
External surface	3	0.5	0.5		0	0.5	1.5	0.375
Gauge pos. slot	1	1	1		1	1	4	1
Ring positioning slot	1	1	1	1	1	1	5	1
Seat support surface	1	0.5	1		0.5	0.5	2.5	0.625
Bottom Surface	1	0.5	1	1	0.5	0.5	3.5	0.7

Description	*Feature Complexity*	*Weighted Feature Complexity*
Valve contact surface	0.125	0.018
Internal Surface	0.097	0.014
External surface	0.097	0.042
Gauge pos. slot	0.222	0.032
Ring posit. slot	0.222	0.032
Seat support surface	0.167	0.024
Bottom Surface	0.133	0.019
Relative Product Complexity		0.180

Product complexity evaluation has been performed by building a matrix specific to the component being evaluated. In Table 3, the complexity matrix for precision forging has been showed in details. Product's main features have been considered for case study's characteristics (e.g. main surfaces and contact zones). The relative effort involved in producing every shape, geometry, tolerances and tolerance stack up has been indicated with a rating (0 low effort, 0.5 medium effort, 1 high effort), for every characteristic (as in the procedure described in ElMaraghy & Urbanic 2003; Kuzgunkaya & ElMaraghy 2006; Wiendahl & Scholtissek 1994)
Surface finish, fillets and defects (unfilled sections and surface cracking) have been investigated as specifications, with similar system. Not all specification parameters have been considered for some valve seat characteristic indicated by empty cells in Table 3 (i.e. slashed) Information number (N=75) and unique information number (n=51) have been used for calculating entropy (8) and diversity measure (9), s0 $\mathrm{H}_{\text{product}} = 6.25$ and $D_{R_{product}} = 0.68$.In Figure 5 (right), final complexity values have been showed, in blue. For example the complexity index is higher in precision forging than in rotary, to reflect the nature of the product geometry and process.
Product redesign step has been applied to the valve seat for improving product quality and decrease manufacturing complexity. Firstly, the surface finish on the external surface is changed (from 0.8 to 0.4 Ra). Assembly requirements are considered and the radius of two external fillets, located externally on support surface and bottom surface, is increased. These fillets do not necessitate strict radius, so their modifications increase their feasibility by forming process. Modifications in compatibility and complexity have been summarized in Figure 5. Regarding complexity, redesign has not changed compatibility for precision range, because the increase in surface roughness still remains in the process capability range. On the other hand for rotary forging, the redesigned roughness is more suitable to be reached within process ranges. Even if roughness improvement has increased complexity for both processes, fillet radiuses increasing have more impact to complexity evaluation. So, precision and rotary forging complexity indexes decrease both after the redesign.

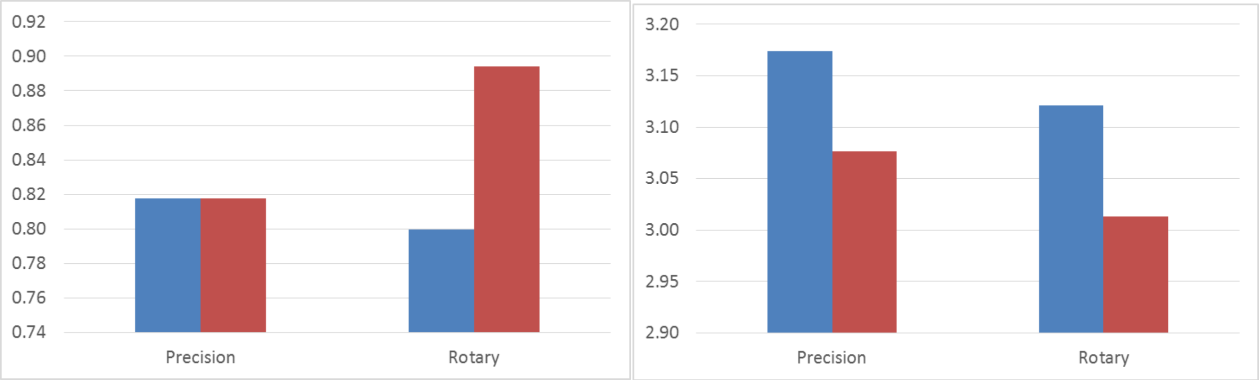

Figure 5: Comparison between precision and rotatory forging compatibility (left) and complexity (right) in the cases original (blue) and redesigned (red) cases.

4. CONCLUSIONS

A hybrid procedure, including compatibility assessment through fuzzy sets and complexity evaluation through matrix development, has been outlined and demonstrated using a case of study. Tolerances and roughness improvements have been detected as design modifications and combined with manufacturing feasibility, to show how an improvement in quality can be also provide advantages for manufacturing. Material selection and several other features have been excluded from the procedure. Further development can directly include them in compatibility characterization, using them in first design phases. This methodology needs to be supported by a bank of information about processes and product. To ensure the screening phase and compatibility stage are accurate for all required features (e.g. evaluating compatibility with material and shape, instead evaluate only their non-feasibility). This methodology is an early stage tool, for dealing with uncertain stages of process and product design. Particularly, combination between design modifications and manufacturing capabilities can be quantified at an early stage, instead generally assessed or excessively detailed (waste of resources).

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