Finding the Optimum Progression Design for Cold Forged Parts

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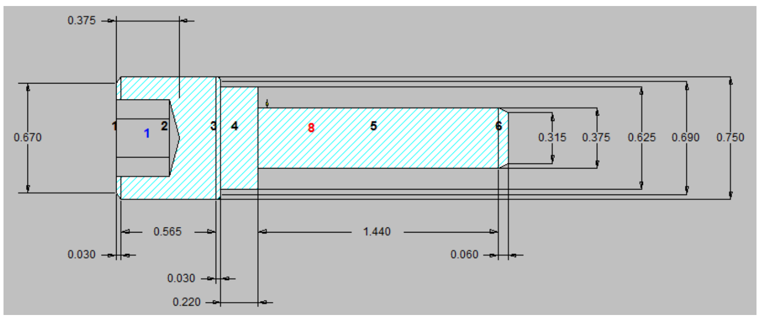
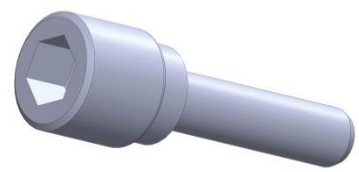
Abstract
The objective of this paper is to show an approach one can take to determine the best progression design for any cold forged part. The progression design, of course, must meet certain basic requirements. The design must fit one of the available forging machines which may be multi station headers or presses. It also must yield a product that meets all the dimensional and quality specifications. For this article, manufacturing of a simple socket head cap screw is investigated.





Three different progression designs with different starting wire diameters are considered. These alternative designs were obtained using the 'NAGFORM' forging sequence design software. The three sequence designs were simulated in NAGSIM.2D / NAGSIM.3D FEA simulation software to predict the forging load, strain distribution in forged part and stresses in selected tools. The results are listed below. The results show that one forging sequence should result in significant lower manufacturing cost compared to others sequences. This is providing the required equipment is available and the part is heat treated after forging. The selection of design would change based on the strength of material being formed.

Introduction
Most cold forged parts are progressively formed on forging machines like multi station headers and presses. The purpose of progressively forging in a number of stations is to control the metal flow so the part can be formed net shape or near net shape. Progressive forging also helps in simplifying the tool design and control of part dimensions. The design of progressively forging of the part is the most important aspect of manufacturing a cold forged part. It defines the major part of manufacturing cost and also the quality of forged part. In general, there are numerous possible forging progressions to cold forge a part. Some of the possibilities come from the fact that the part can be manufactured starting with different wire diameters.

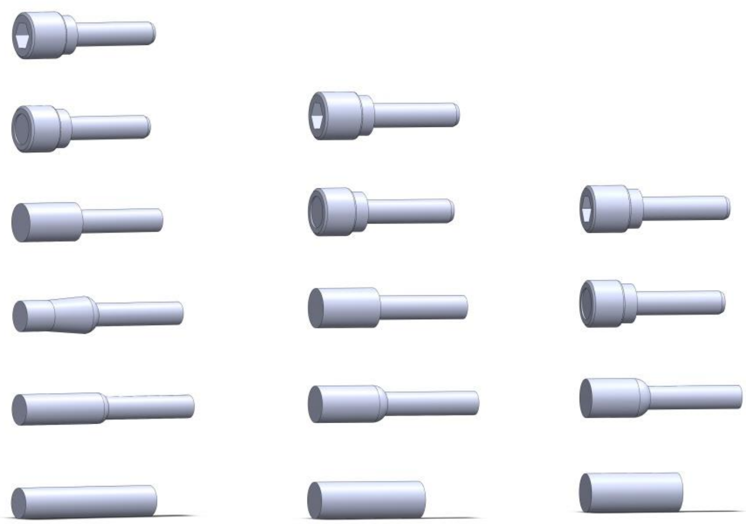
With all these possibilities of alternative sequence designs, the question arises as to which design out of these possibilities is the best design. Some designs get eliminated on the consideration that the forging machine required for a possible sequence is not available. Still there remain a number of possibilities of progression designs that may be chosen.

In practice, the designer develops a sequence design based on past experience. In most cases when the part material and shape is similar, the design is likely to be a reasonably good choice. However, if the part shape changes or the part material is different, the design which the designer is likely to use may not be the best design. In order to find the optimum design, the designer must be able to design alternative sequence designs for a part and also be able to evaluate these alternatives to find the best. Software such as NAGFORM program for sequence design allows the designer to come up with alternative designs in a few minutes. The validity of the selected designs can be checked in a FEA simulation program such as NAGSIM. If the simulations can be performed in a 2D simulation program which does not take much time, evaluation of alternatives designs becomes feasible.

Example Part
The part considered is a simple socket head cap screw. The shape is slightly different than typical cap screws in that it has another round head behind the normal head with the HEX drive. For the purpose of demonstration, the part material is assumed to be a low carbon steel such as AISI 1010 that can be heat treated if higher strength is required. We would later compare the designs when the part would not be heat treated after forging. For that case, the material is assumed to be a slightly harder material such as AISI 1035.

Alternative Sequence Designs

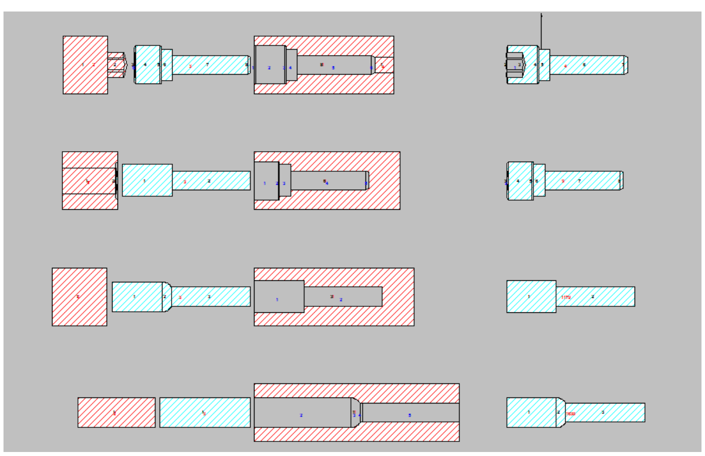
NAGFORM program is used to give different alternative designs for this part. The three alternative forging progressions chosen for evaluation are shown below. The design # 1 is with a wire diameter of 0.494 inches. It requires five stations to cold forge the part as shown. The design # 2 is with the wire diameter of 0.576 inches requiring four stations to form as shown. The last design is with a wire diameter of 0.618 inches and requires only three stations to forge the cap screw. The designs given by NAGFORM program or by any designer need to be validated by actual testing using hard tooling or using FEA simulation. In this case, a simulation software (NAGSIM) was used to perform a comparative study of the designs.



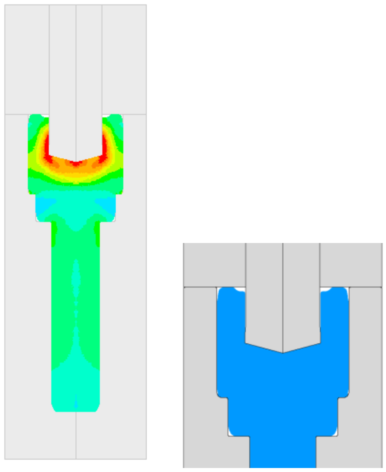
Design # 1 ***Design # 2*** ***Design # 3***

Evaluation of the Forging Sequences

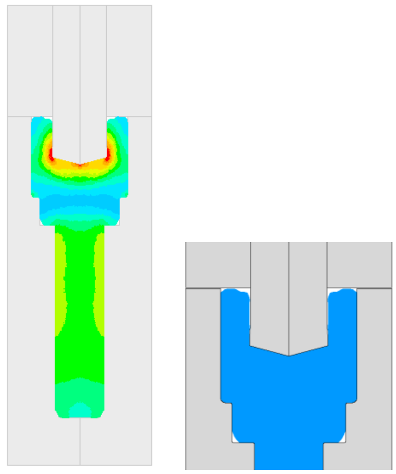
To simplify the process of simulation, the Hex drive of the part is replaced with a round hole as shown. The three forging sequences are simulated using the 2D simulation program NAGSIM.2D. The NAGFORM program automatically creates a 'generic' tooling for its designs. The tooling created by NAGFORM was slightly modified and used for simulation. The tooling created automatically by NAGFORM program for Design # 2 is shown here.



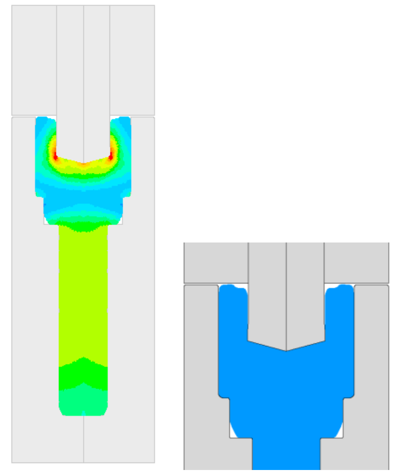
The pictures show the simulation of the three sequence designs. The result displayed is the effective strain in the part as a result of cold forging process. The starting wire is assumed to be annealed with no prior strain from wire drawing.



Design # 1



Design # 2



Design # 3

Design Comparisons							
	Units	Using Material AISI 1010			Using Material AISI 1035		
		Design 1	Design 2	Design 3	Design 1	Design 2	Design 3
Starting Wire Diameter	Inches	0.494	0.576	0.618	0.494	0.576	0.618
Number of Station	Na	5	4	3	5	4	3
Total Load	Pounds - lbs	193010	152650	124260	239340	199810	159500
Energy (approximate)	lbs - in	47847	44223	35926	61283	57854	45548
Forging Stroke	Inches	0.975	0.768	0.708	0.975	0.768	0.708
Maximum level of strain in head	Na	2.84	2.56	2.24	2.66	2.44	2.09
Maximum level of stress in extrude pin	Ksi	384	384	346	461	461	415

a. **Final Part Shape -** The simulation shows that generally the final part shape and dimensions can be obtained by all three designs. There is slightly more non fill at the corner for Design #3.

b. **Number of Operation Required -** It is desirable to have the minimum number of stations to cold forge a part. This is because of lower manufacturing costs including the forging machine cost, tooling cost and higher productivity associated with machines with fewer stations. So design # 3 is a better design with 3 stations compared to design # 2 with 4 stations and design # 1 requiring 5 stations.

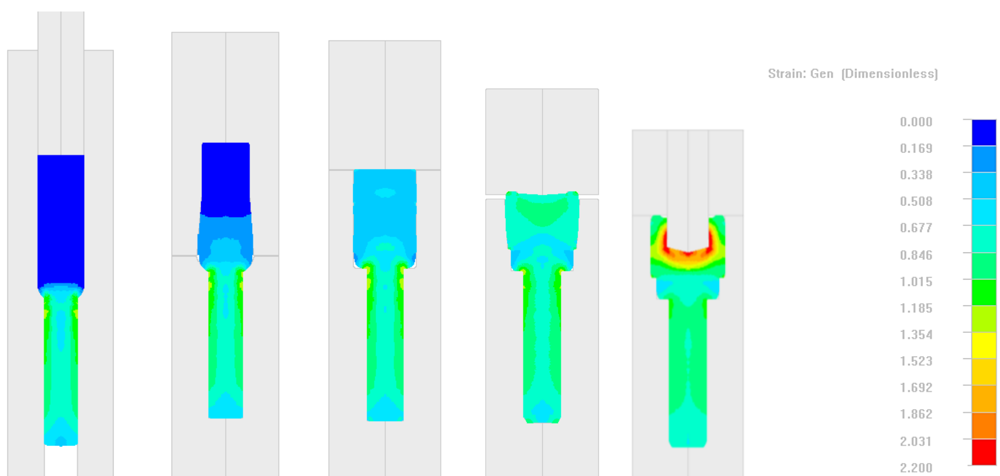
c. **Forging Load and Energy required -** A typical load stroke curve for the complete forging sequence is shown below. This represents the combined load stroke curves of various individual operations. In general, combining the forging operations reduces the forging load, though it may not reduce the energy required per cycle. Here again, the progression design # 3 shows the lowest forging load required to cold forge this part, followed by design # 2 and then design # 1. Design # 3 is the best design from the point of view of requiring a machine with lower tonnage.

The energy required to form the part is given by the area of the load-stroke curve. The approximate values are given in the table above. Again, the design #3 takes the least amount of energy to cold forge the part.

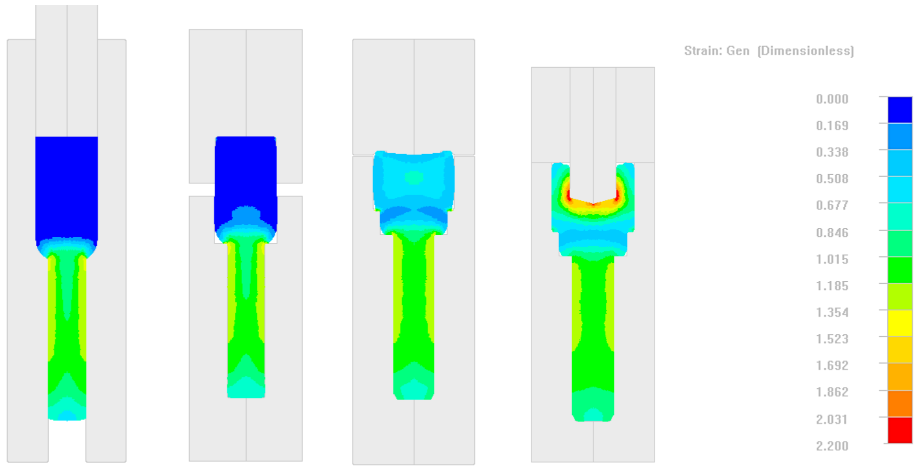
Design # 3 – Total Load Stroke Curve using NAGSIM.2D

d. Work Hardening of Forged Part - Material hardens as it is deformed at cold forging temperatures. The hardening of the material termed work hardening depends upon the amount of deformation called strain and the work hardening characteristic of the material represented by its true stress-true strain curve. The amount of deformation represented by Effective strain ‘ Eeff’ depends primarily upon the change in shape in forming processes. The true stress-true strain curve for the material (obtained through a Compression Test) is an input required for simulation. It is commonly represented by an equation called Constitutive equation of form

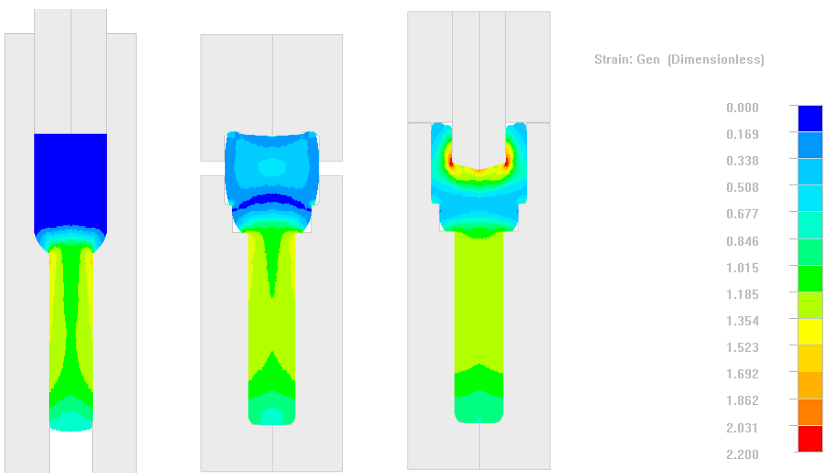
$$\sigma = k\varepsilon^n$$



Design # 1 – Effective Strain at the end of each station.



Design # 2 – Effective Strain at the end of each station.



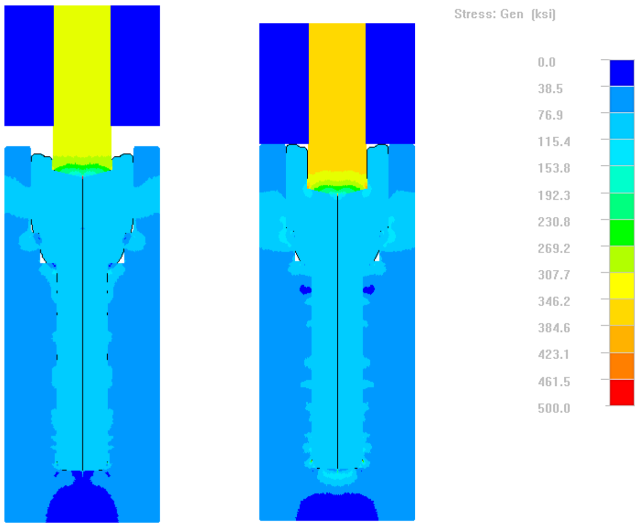
Design # 3 – Effective Strain at the end of each station.

The pictures below show the effective strain distribution in the forged part for the three forging sequences. For the purpose of showing the difference in strain distribution, the scale for the strain, which is a dimensionless quantity, is kept 0-2.20 for the three plots. The maximum values of the strain in the three designs, however, differ and are shown in the table. As it can be noticed, the strain in the socket head portion is the lowest with the larger wire size of design # 3. This is to be expected as the change in diameter for the starting wire diameter to the socket head diameter is least with the largest wire diameter. There is a limit on the maximum strain that a material can take. Putting more strain than material's formability limit can result in cracking of the forged part. The forging sequence design must ensure that the total strain at any location of the part does not exceed the material's limit.

Work hardening of forged part can be detrimental as well as beneficial depending upon the part strength requirement and heat treatment. The higher the work hardening, higher is the strength of the material as forged. If the forged part is used without heat treatment, work hardening can be beneficial. However, higher the work hardening, greater is the force required to deform the material further. Thus the stresses in the tools go up as the part work hardens which decreases the tool life. The picture shows the Effective yield stress 'Seff' also called flow stress distribution for the cold forged part of Design # 3.

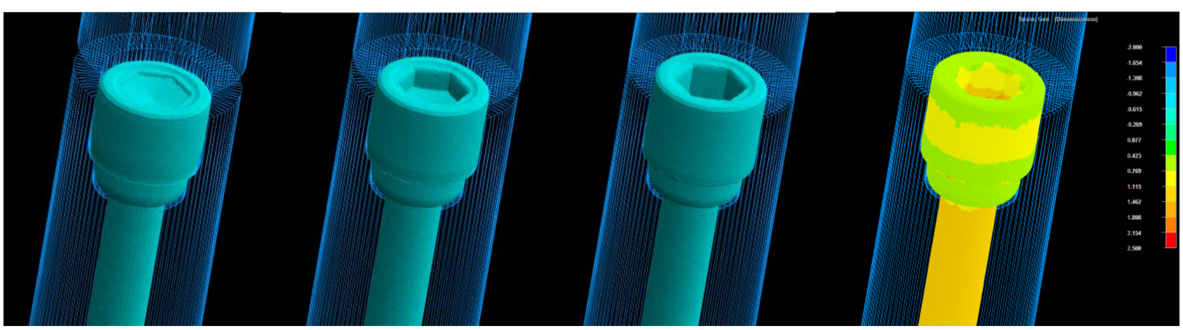
In Design # 1, the strain distribution in the socket head is more than that in Design # 2 which is more than that in Design # 3. The reverse is true for the strain distribution in the shank portion. The same is true for the work hardening as represented by the effective stress. This implies that the tool stress in extrusion pin would be least for Design # 3.

e. **Tool Stresses in Extrusion Pin -** The picture shows a typical distribution of effective stress in Extrusion Pin for the three designs. The picture is for Design # 3. The maximum value of stress across the cross section of the extrusion pin is listed in Table 1. Clearly, the tool stresses in extrusion pin of Design #3 are less than that in Design # 2 and in Design # 1.



f. **Effect of Part Material –** With a harder or more work hardening material than AISI 1010 material, the values of load and energy required, part stresses and tool stresses would go up. The increase would be proportional to the change in true stress–true strain curve of the two materials. To demonstrate this, the simulations were repeated with AISI 1035 material for the part. The various values are listed in the Table. Load, energy and tool stresses go up by 20-30 % when the material is changed from AISI 1010 to AISI 1035. Even if the forging machine is available to cold forge this part with any sequence design, the tool stresses may now dictate the design with least tool stresses be used to keep the tool life and cost within acceptable limits.

g. **Extrusion of Hex Drive Hole-** We simplified the comparative evaluation by replacing the Hex hole with an equivalent round hole so the simpler 2D simulations could be performed for the last operation. This simplification is not expected to change the forging loads, average strain and flow stress as well as the tool stresses by much. However, the material fill at the hex corners and the strain distribution around the Hex profile cannot be accurately simulated by 2D simulation. Picture shows a 3D simulation of the back extrusion with a Hex pin for reference.



Selection of Sequence Design
For this particular part, Design # 3 seems to be the best design among the three designs provided (a) the required equipment that can accommodate wire diameter of 0.618 inch was available (b) the part was going to be heat treated after cold forging or the part strength as forged was acceptable. Please note that there is no general sequence design that would be the optimal for this type of part for all conditions. If the equipment to accommodate the larger diameter was not available, then Design # 3 would not be an option. If the material of the cold forged part was a high strength material such as AISI 4140 or stainless steel and the cold forged part was used as forged, the design would have to be the one that work hardens the socket head to the strength level. The optimal sequence design for those conditions can be different. For all different requirements, the approach given in this paper to come up with alternative and then evaluating those through simulation can be used.

Closing Remarks
In this study, for the sake of keeping it simple, we have not given consideration to many factors that may play a deciding role in selection of the forging sequence. One such factor is the amount of non-fill in the forged part. For example, the simulations show that with Design #3, there is more non-fill at the corner of the middle section compared to the other designs. If the part

specification did not accept the amount of non-fill, this design would have to be either improved by change in design or adding another operation or be replaced by Design # 2 or Design #1. NAGFORM also gave a design similar to #3, but with an additional operation of squaring up of the corner. For certain parts, the cold forging process involves stretching the surface of the part to the extent that the material cracks at the surface during or after forging. For such parts, 'Tensile Damage' must be considered in the forging sequence. For some parts, the desired grain flow in the forged part is a specified requirement. All these can be studied using the FEA simulation program.